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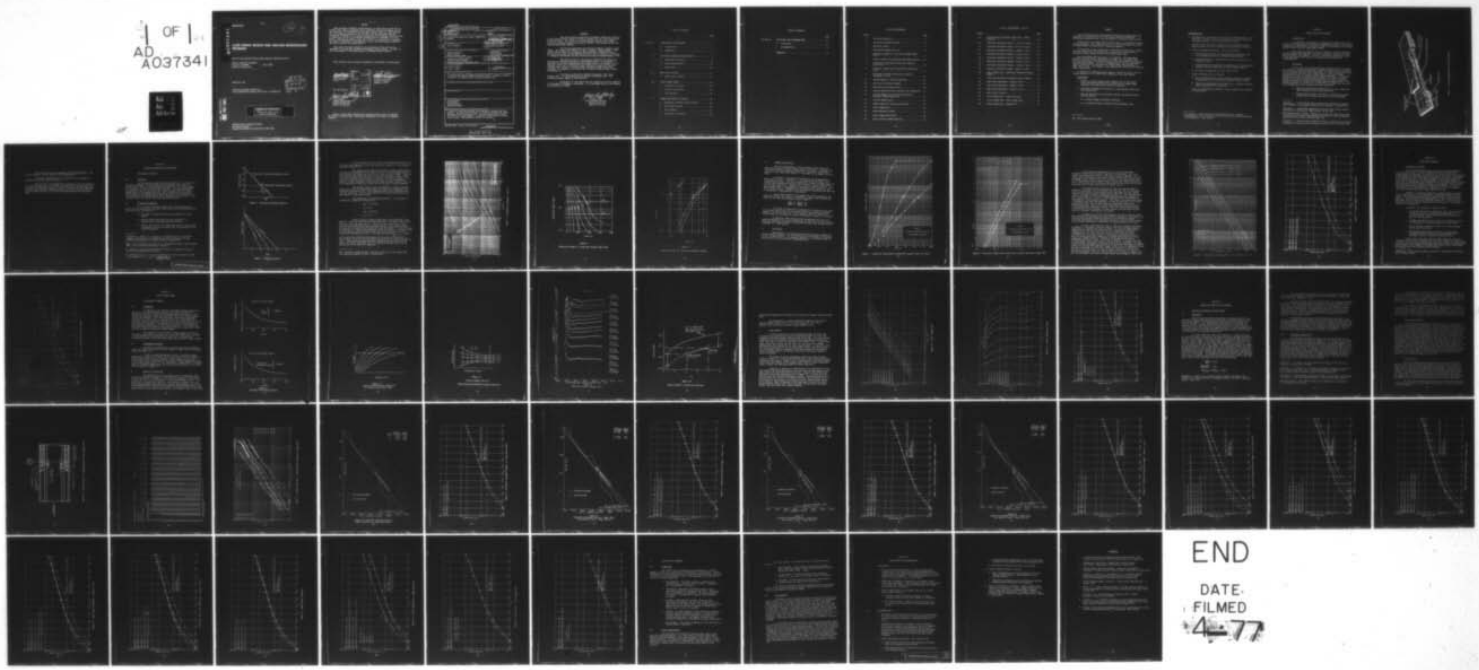

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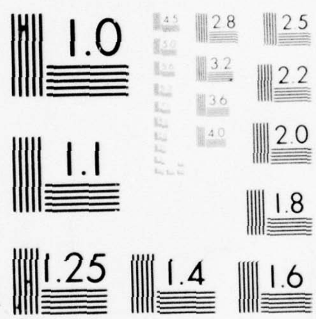

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A-37B FATIGUE SENSOR DATA ANALYSIS METHODOLOGY PROGRAM

DEPUTY FOR SYSTEMS SPECIALIZED AIRCRAFT PROGRAM OFFICE

CESSNA AIRCRAFT CO~~MPANY~~
WALLACE DIV~~ISION~~
WICHITA, KANSAS 67201

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For the Director

James R. Stanley

JAMES R. STANLEY
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A feasibility study was conducted on two methods of fatigue sensor data analysis. The first method constructs an equivalent straight line strain exceedance history from sensor data. The second method converts sensor data directly to fatigue damage. A technique is discussed for the effect of mean strain. Both methods are shown to be feasible.

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FOREWORD

This data analysis methodology development program was conducted by the Cessna Aircraft Company of Wichita, Kansas under Air Force Contract No. F33657-71-C-0163. The contract was initiated under project A-37B (335A) "A-37B Final Fatigue Program", and Task No. P00034, "A-37B Fatigue Sensor Data Analysis Methodology Program."

The work was supervised and directed by Robert W. Walker, Group Leader. This report was prepared by John Y. Kaufman, Design Engineer. This project was initiated by Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, and was administered under the co-ordination of Richard C. Culpepper (ASD/SD27MS) Aircraft Structural Integrity Program Manager, A-37B.

The previous report of this series, ASD-TR-75-33, reports the results of an extensive testing and data analysis program to establish a data base for the Micro-Measurements FM Fatigue Sensor. The purpose of this follow-on effort was to develop practical methods of using that date base. Although other concepts of fatigue damage calculations might have been practical, all damages in this report are calculated using the SNK_f concept of Reference 8.

This report covers work conducted from August, 1974 until October, 1975. It was submitted by the author in February, 1976. The contractors report number is 318E-7616-061.

Publication of this report does not constitute Air Force approval of the reports' findings or conclusions. It is published only for the exchange and stimulation of ideas.

James R. Stanley

JAMES R. STANLEY
Colonel, USAF
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Deputy for Systems

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SUMMARY

The A-37B Fatigue Sensor Data Analysis Methodology Program report was prepared per requirements of the A-37B Fatigue Sensor Data Analysis Methodology Program and under the authorization of Contract F33657-71-0163.

Traditionally the fatigue sensor has been used as a comparative fatigue loading indicator. This required the use of a model from either test data or predetermined load spectrum for comparison purposes.

The objective of this program was to establish the feasibility of data analysis methods which would determine an approximate strain history or structural fatigue damage directly from fatigue sensor data.

Two such methods have been shown to be feasible. The "Equivalent Exceedance History Method" establishes a straight line exceedance curve which is equivalent to the applied strain history and produces approximately the same fatigue damage. The "Direct Damage Method" uses the data from a single fatigue sensor to determine the fatigue damage corresponding to a known value of K_f[a]. This damage is then adjusted for the K_f of the structure under investigation.

In addition, an investigation was made of a method to account for the fatigue damage due to the mean strain component of the load history.

Conclusions:

1. Methods to relate fatigue sensor response, ΔR, to the cyclic strain spectrum producing that response and to fatigue damage produced by the same cyclic strain are feasible.

2. Additional refinement is necessary to these methods before broad scale application.

3. With the application of the methods derived, the fatigue sensor could be used as:

   a) A fatigue damage accumulation indicator

   b) An economical means to develop strain exceedance data

---

[a] K_f - The fatigue severity index.

Recommendations:

1. Instrument each new production aircraft with fatigue sensors. This data could be used to aid in the disposition of future structural integrity problems or formulating inspection policy.

2. Install fatigue sensors on a sample of USAF Continental United States aircraft for field verification and application refinement.

3. Refine and computerize methods. This would include:

   a) Preparing more accurate ΔR versus maximum strain/slope table for the application of the Exceedance History Method.

   b) Developing methods to establish the effective multiplier of an installed sensor.

   c) Computerizing and documenting the application of the Equivalent Exceedance History Method and the Direct Damage Method.

   d) Refining the application of mean strain effect.

4. Conduct laboratory tests to obtain:

   a) Basic performance data on high multiplier FM sensors required by application of the Equivalent Exceedance History Method.

   b) Temperature compensation and "creep" data on improved adhesive/sensor combination (M-17 adhesive[b]).

5. Study the feasibility of methods to relate fatigue sensor response to crack growth.

---

[b]M-17 Adhesive - Was developed by Micro-Measurements as a possible replacement for M-16 in an effort to solve the "creep" problem encountered in the Reference 3 test program.

SECTION I

INTRODUCTION AND BACKGROUND

A INTRODUCTION

The purpose of this report is to present the findings and results of the A-37B Fatigue Sensor Data Analysis Methodology Program. This was work conducted per requirements of Reference 1 under the authorization of Contract F33657-71-0163, Contract Change Number P00034.

This report is organized into six sections. Section I contains the introduction and background. Sections II through IV describe the data analysis methods investigated. Section V presents the summary and results of the investigation and Section VI discusses the conclusions and recommendations.

B BACKGROUND

The A-37 Aircraft Structural Integrity Program (ASIP) has served as a vehicle to evaluate commercially available fatigue sensors for application to aircraft structural fleet monitoring. An initial program (Reference 2) was conducted 1971-1972 using A-37B laboratory tests and sixteen operational aircraft to evaluate fatigue sensor performance. This program indicated that the Micro-Measurements FM Sensor[a] (see Figure 1) showed promise as an aircraft structural monitoring tool and that a laboratory program was needed to develop basic fatigue sensor performance data. This program (Reference 3), carried out in 1973-1974 established this data base. The recommendations which resulted from this effort were:

1. Extend FM fatigue sensor operation over a broad temperature range compatible with aircraft operations.

2. Investigate both direct and indirect relationships between fatigue sensor response and aircraft structural damage.

Reference 1. - "A-37B Fatigue Sensor Data Analysis Methodology Program", Work Statement, Cessna Report 318E-7419-017A, Revision A, 29 April 1974.

Reference 2. - "Program for Evaluation of Annealed Foil Fatigue Sensors", Final Report, Cessna Report 318E-7219-029, 30 June 1972.

[a]Micro-Measurements FM Sensor - Denotes the fatigue life gage (trade name) installed on an FM strain amplifier and manufactured by the Micro-Measurements Division of Vishay Intertechnology, Inc.

Reference 3. - "Fatigue Sensor Evaluation Program - Laboratory Test Report", Aeronautical Systems Division Technical Report ASD-TR-75-33, October 1975.

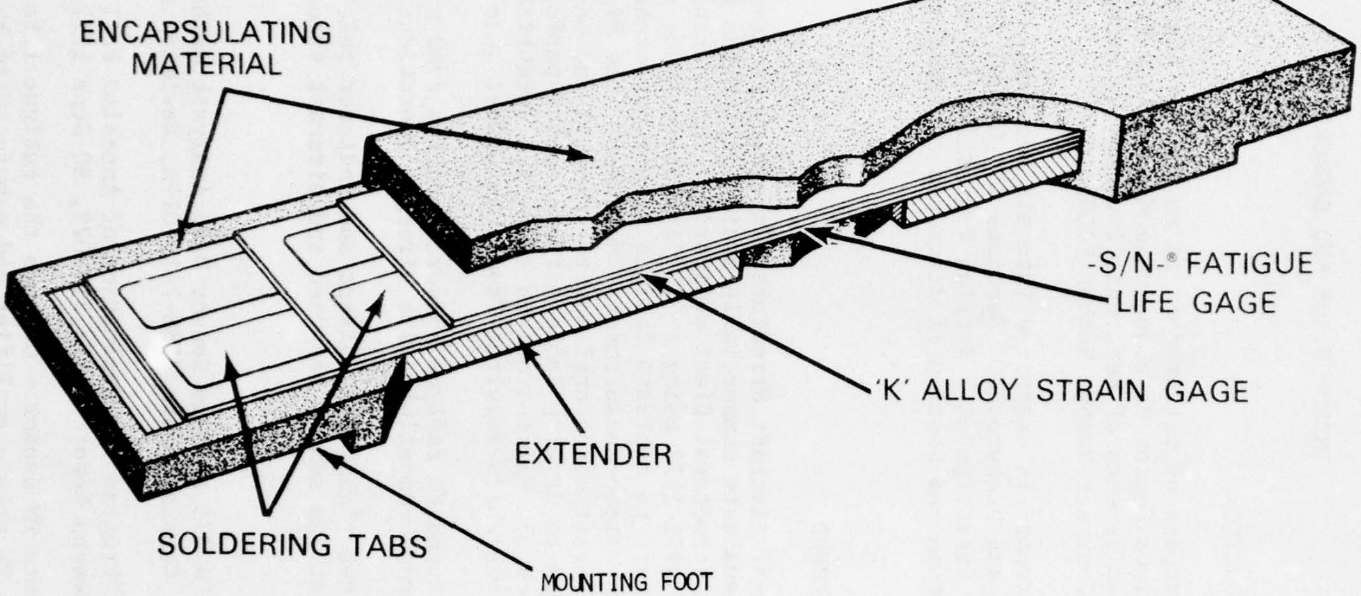

Figure 1 - Micro-Measurements FM Fatigue Sensor

The first objective was undertaken by Micro-Measurements. The new M-17 adhesive was one result of this investigation.

The second recommendation was contracted by the Reference 1 program of which this report is a part.

The results of this program have continued to show the potential of the FM fatigue sensor for aircraft fleet monitoring with the ability to establish the usage load spectrum as well as to monitor directly individual aircraft fatigue damage. Program technical effort and concept evaluation have been under the direction of ASD of Wright-Patterson Air Force Base, Ohio.

SECTION II

EQUIVALENT EXCEEDANCE HISTORY METHOD

A DESCRIPTION OF METHOD

A-1 Objective

The data analysis method outlined in Reference 4, constructs an equivalent straight line alternating strain exceedance curve based on fatigue sensor data. In the discussion of this method, all cyclic strains are assumed to be fully reversed (mean strain=0). This curve approximates the exceedance curve of the actual input spectrum, and produces fatigue damage equal to the original spectrum. Such a straight line curve may be fully defined by the maximum strain (Emax[a]) and slope (h[b]), see Figure 2. The objective of this investigation was to determine the feasibility of this analysis method for aircraft fleet monitoring applications.

A-2 Principal of Analysis

If two or more FM fatigue sensors with different multiplier ratios (n[c]) are subjected to the same strain history, the following relationships will exist (see Figure 3):

1. The number of applied cycles will be identical for each sensor.

2. Maximum strains experienced by each sensor will be proportional to the sensor multiplier values.

3. From 1. and 2. above, it follows that slope of the effective exceedance curve for each sensor will be proportional to the sensor multipliers.

Reference 4. - Sheth, N. J., Bussa, S. L. and Nelson, M. M., Ford Motor Company, "Determination of Accumulated Structural Loads from S-N Gage Resistance Measurements", SAE Paper 730139, 8 January 1973.

[a]Emax - On the straight line curve of the Equivalent Exceedance History Method, Emax is the strain in microstrain at one cycle.

[b]h - Slope of the Equivalent Exceedance History Line measured as change of strain in microstrain per log cycle.

[c]n - Multiplier ratio is the strain amplification factor produced by the FM strain amplifier and is equal to $\frac{\text{sensor strain}}{\text{specimen strain}}$.

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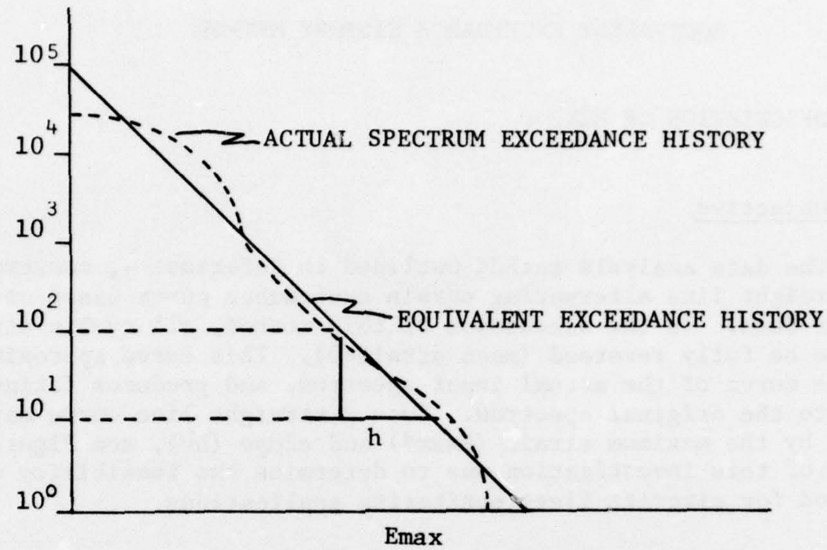

Figure 2 - Equivalent Exceedance History

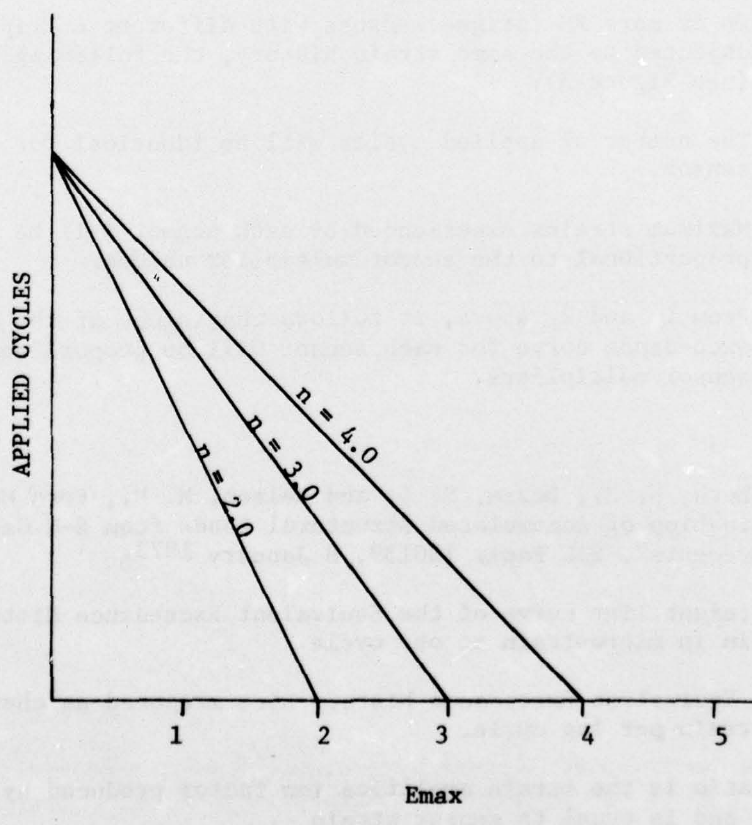

Figure 3 - Multiplier Ratios

It also follows that these same relationships will hold true for the structural component on which the sensors are mounted if it is assigned a multiplier value of 1.0.

Each combination of Emax and h defines a unique strain spectrum. This spectrum as modified by the effective value of strain multiplication of the FM sensor will produce one and only one value of Delta R (ΔR^d), although other spectra exist which will produce that same resistance change. Using the sensor response data developed in Reference 3 and shown in Figure 4, the response prediction method of Appendix A Reference 2, may be employed to generate a table (resistance change matrix) which provides a Delta R value for each combination of Emax and h across the useful range of these parameters.

The computer program listing in Reference 4 defines a program which, given a set of ΔR/multiplier data, will search and interpolate this resistance change matrix for a slope/Emax/multiplier ratio combination which fits the input data. This in turn identifies the strain spectrum which has been applied to the base structure.

This method may be illustrated graphically. For purposes of illustration, assume the following data:

$$\Delta R_1 = 2.20 \text{ ohms}$$

$$n_1 = 3.5$$

$$\Delta R_2 = 0.58 \text{ ohms}$$

$$n_2 = 2.0$$

A plot is made of constant Emax lines versus slope and ΔR (see Figure 5) using data from the table generated above. A constant Delta R line will then cross each Emax line at a slope value which identifies a strain spectrum which would produce that resistance change. This constant Delta R line may then be reploted versus Emax and slope (see Figure 6). This procedure is followed for a second (and subsequent) values of Delta R. A 45° line (remember that Emax and slope are both proportional to the multiplier ratio) is constructed originating at Point A. The multiplier ratio $\frac{3.5}{2.0} = 1.75$ is laid out on either the vertical or horizontal axis in order to locate Point B. The distance A-B on the 45° line defines the points (A'-B') on the ΔR_1 and ΔR_2 lines. These points give Emax and slope values which when divided by the sensor multiplier value will yield the Equivalent Straight Line Spectrum experienced by the structural component.

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[d] ΔR - Resistance change in ohms. Generally assumed to be the change from the resistance measured at time of installation.

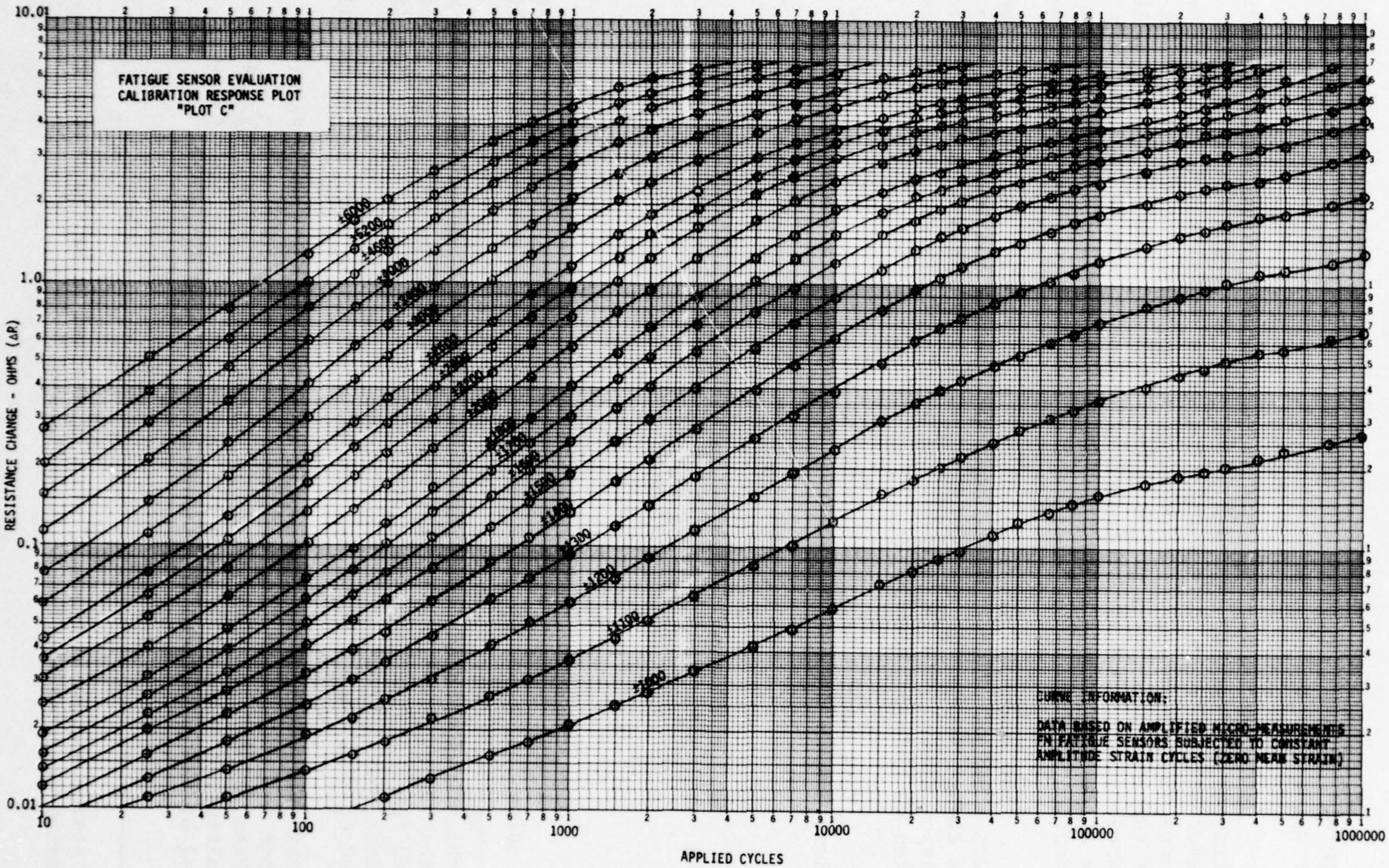

Figure 4 - Calibration Response - Plot "C"

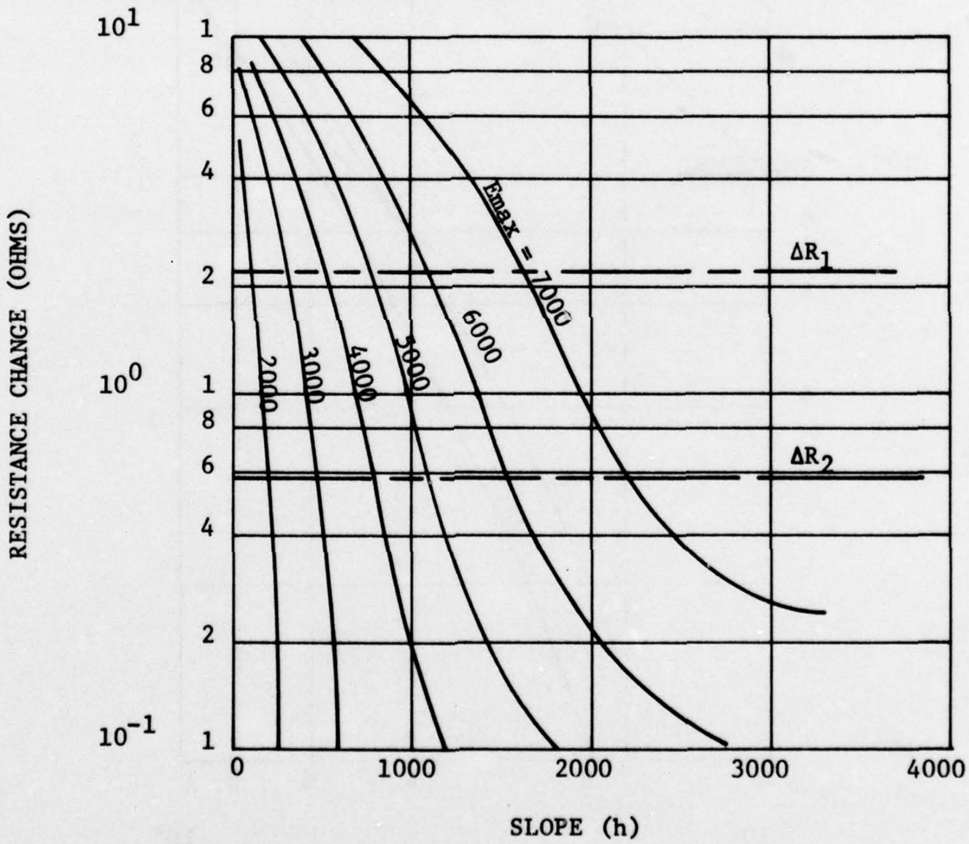

Figure 5 -

Resistance Change V.S. Slope With Constant Emax Lines

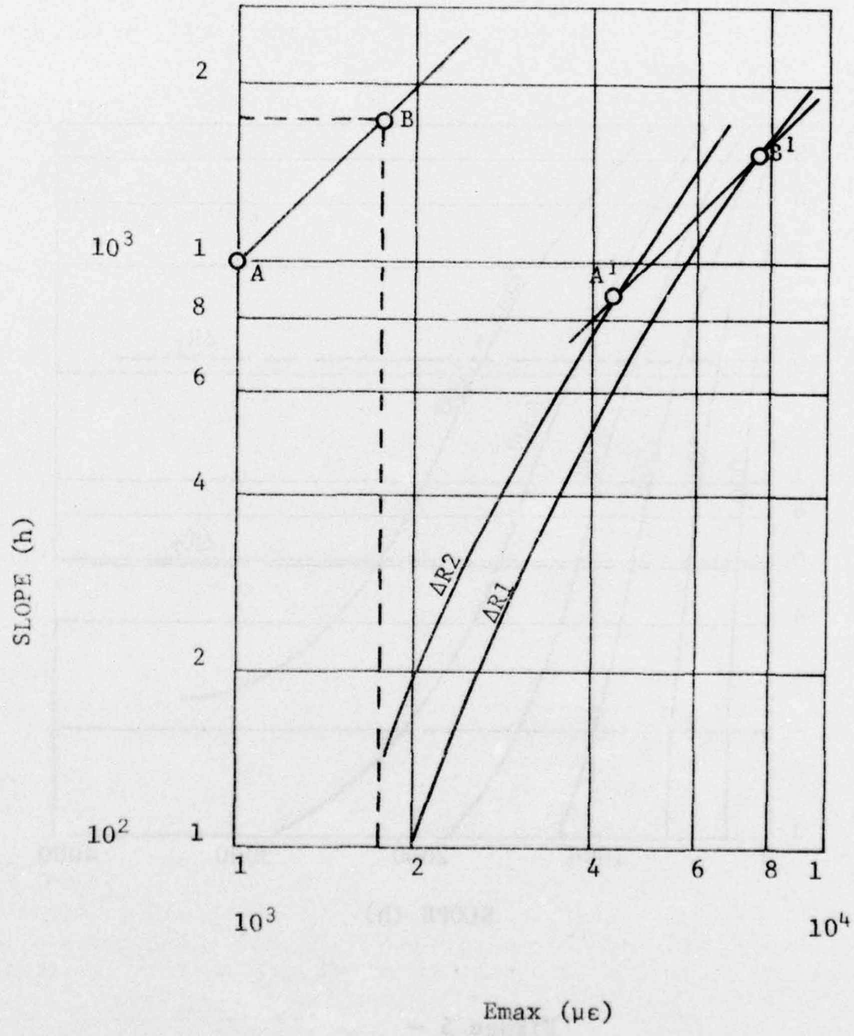

Figure 6

Graphic Solution For Equivalent Exceedance History

B PROGRAM MODIFICATION

For this investigation, a new resistance change matrix was constructed using the sensor response data of Reference 3. Although this table was developed by graphical means which, in general, limited the accuracy to two significant figures, it was judged to be adequate for this study.

The heart of this method of analysis is the interpolation of values from the table. Therefore, a close examination was made of the interpolation process. The first interpolation is made by holding slope (h) constant and interpolating between table ΔR values to obtain Emax values for the input data ΔR's. A sample of this data is shown in Figure 7. This data indicated that a semilogrithmic relationship would produce the most nearly linear results. Therefore, the interpolation subroutine was rewritten to incorporate a semilogrithmic interpolation.

In the second phase of the program, ΔR is held constant at the input data values, and a search is conducted for Emax, slope combinations which fit the basic relationships shown in Figure 3:

$$\frac{\text{Mult. } 2}{\text{Mult. } 1} = \frac{\text{Emax}_2}{\text{Emax}_1} = \frac{h_2}{h_1}$$

The search is conducted in increments of h which may be selected by the user, and the best fit is selected using least squares techniques. A sample of the form of data used in this search is shown in Figure 8 as a justification for retaining the log-log interpolation feature in this search.

In addition, double precision was incorporated into the interpolation subroutine as an aid in determining the best match in those cases in which the difference in effective multipliers is small (see discussion under paragraph 2.3 - Application).

C APPLICATION

Traditionally, the fatigue sensor has been used as a comparative fatigue loading indicator. In this application the multipliers are selected so as to be high enough to give adequate response in a reasonable length of time and still as low as possible for maximum life.

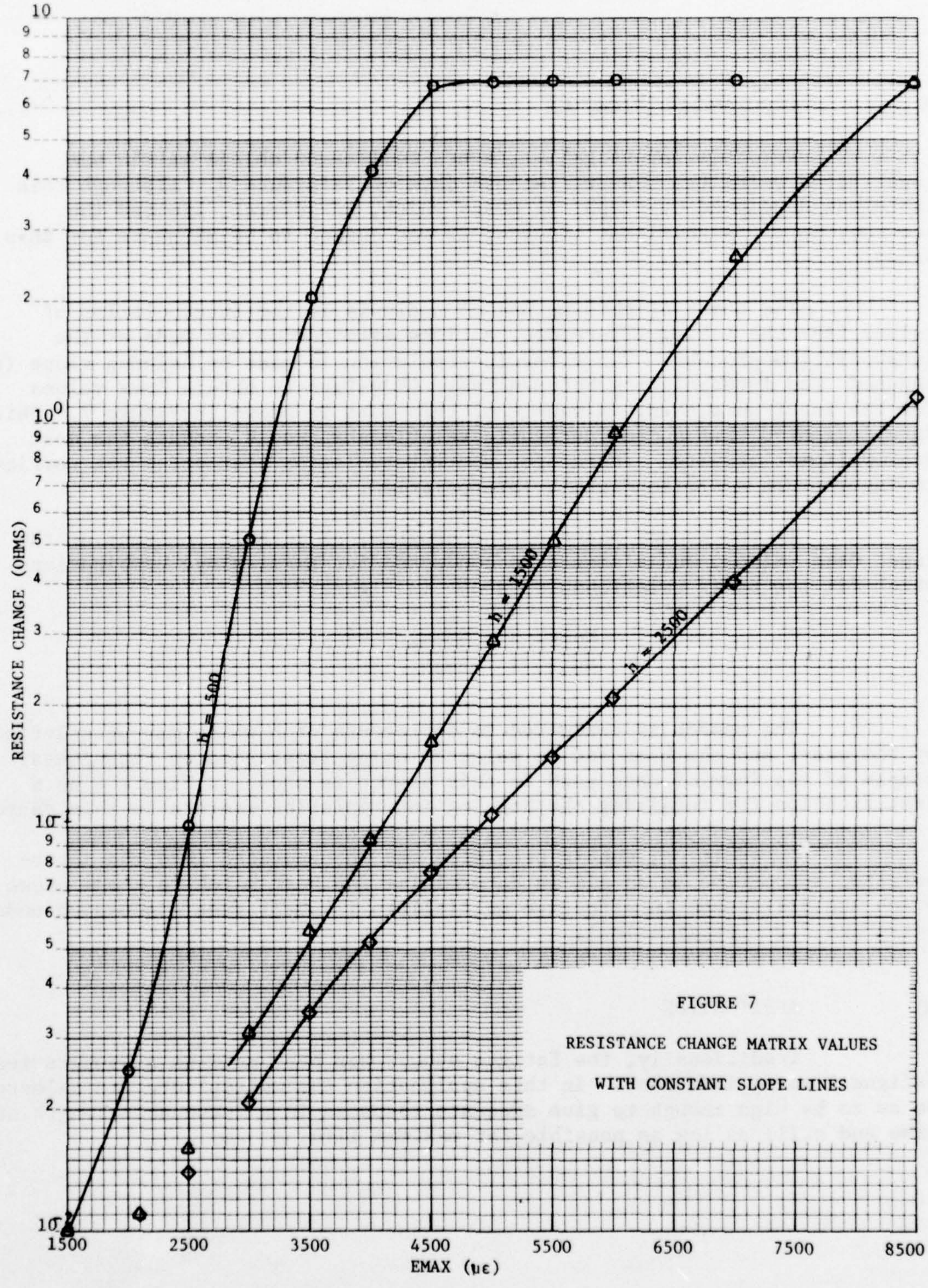

Figure 7 - Resistance Change Matrix Values With Constant Slope (h) Lines

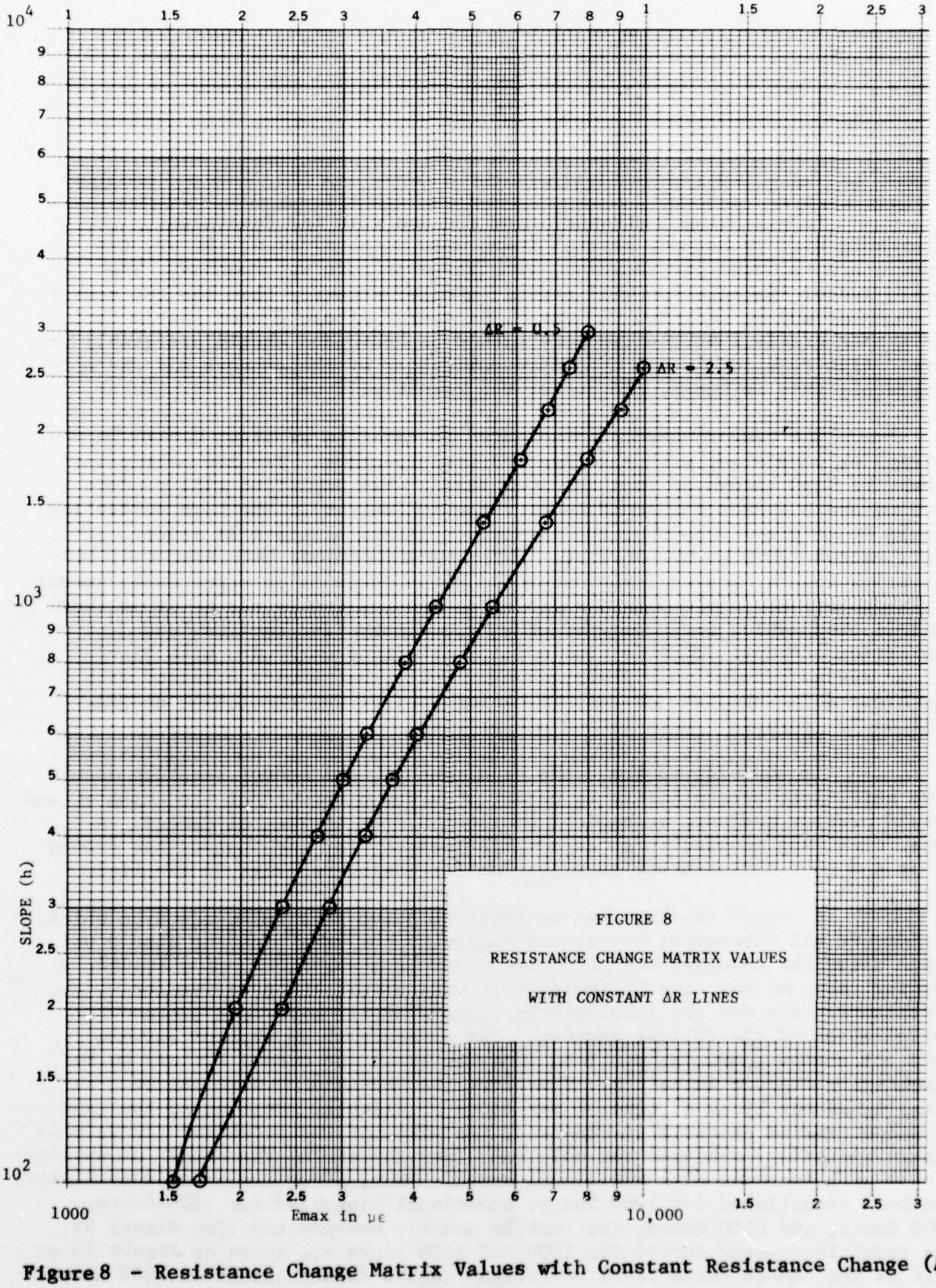

Figure 8 - Resistance Change Matrix Values with Constant Resistance Change (ΔR)

In selecting instrumentation for use with the Equivalent Exceedance History Method, several items must be considered. First, two sensors are required per location, with three or more recommended. The triple sensor installation will provide greater accuracy than the two sensor arrangement and in addition will still be useful if one sensor should fail. The strain gradient between sensors should be known and should preferably be zero. Also required is the effective multiplier of the sensors and the more accurately this is known, the better the result will be.

The sensors should be selected to have the greatest spread in multiplier consistent with the expected load spectrum. The low multiplier should be high enough so that specimen strain when amplified will produce strains above sensor threshold (approximately 1000 $\mu\varepsilon$). The high multiplier should be selected such that the maximum amplified strain will seldom, if ever, exceed +7000 $\mu\varepsilon$ or -5000 $\mu\varepsilon$. These considerations have hampered the investigation of data analysis methods. While there is an appreciable amount of laboratory and field data available, to date virtually all of it is from installations which were designed under the comparative fatigue load monitoring concept. That is, low multiplier values were used with little if any spread between multiplier values. While the results obtained with the older data have been useful, it cannot achieve the consistent accuracy that an "on purpose" installation can provide.

In addition to the above requirements, the sensor location should have sufficient accessibility to permit accurate placement of the sensors, and should provide adequate mechanical protection from accidental damage. A three wire plug mounted in an accessible location for each sensor has proved to be the most satisfactory installation for taking readings in the field.

A "zero" reading must be taken to serve as a reference from which to measure all subsequent resistance change. The "zero" reading should be taken after the adhesive has cured and prior to the sensors being loaded. A reading taken at any time following this will establish an equivalent exceedance curve for the total strain history of the structure since installation of the fatigue sensors. For aircraft whose type of service does not change appreciably, field data has shown the strain history to be essentially ergodic in nature. Therefore, an exceedance curve may be established per block of time or per block of flights. So long as the type of usage remains essentially constant, the slope of the exceedance curve will remain virtually unchanged and only Emax (and therefore, the number of applications) will increase with additional usage. Thus, after the exceedance history has been established for 1000 hours, additional histories for 2000 hours, 4000 hours, and 6500 hours, etc. may be quickly constructed (See Figure 9). The resulting damage curves for 1000 and 2000 hours are shown on Figure 10 as well as the damage curve based on fatigue sensor data readings at 2000 hours.

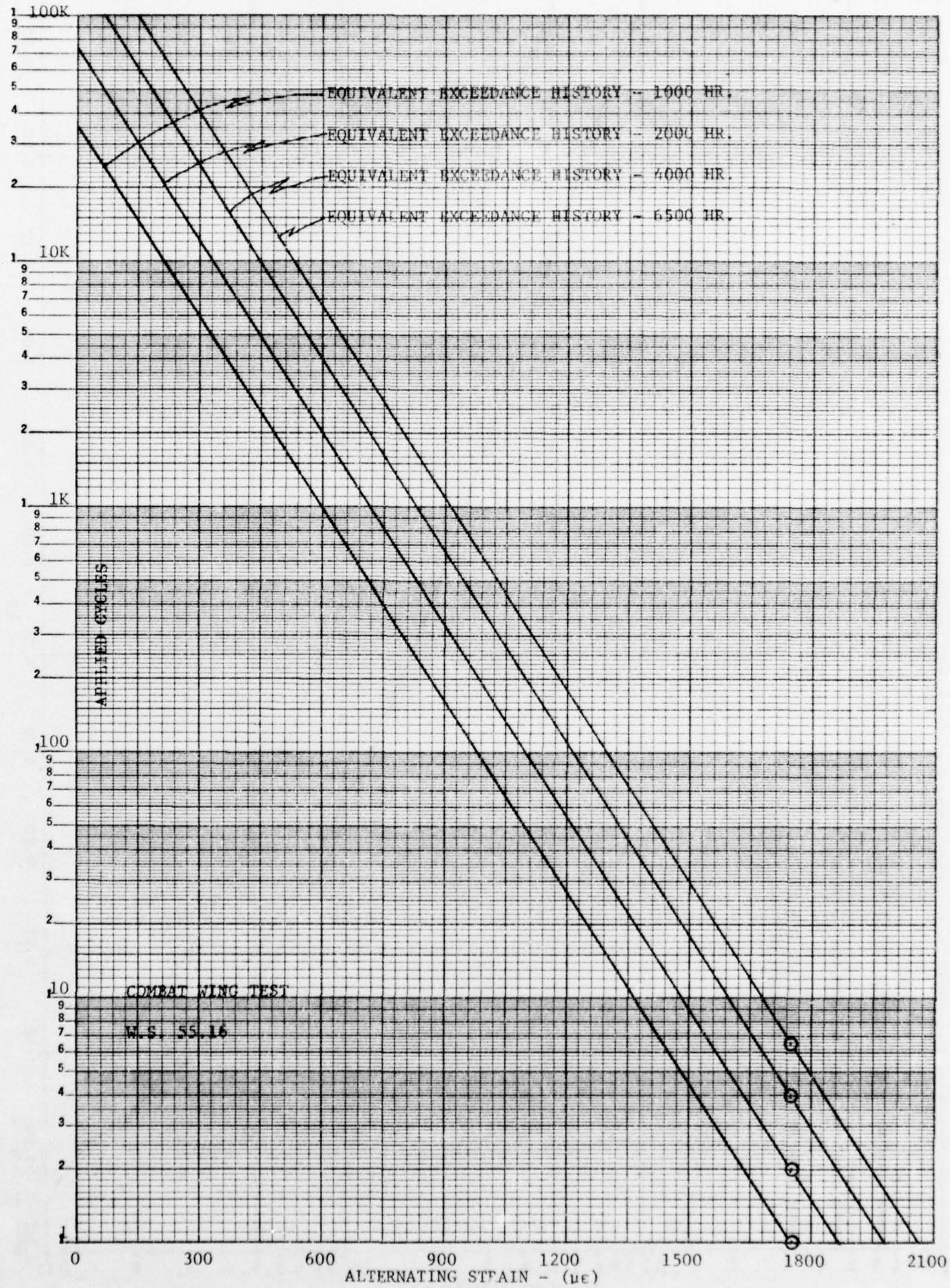

Figure 9 - Equivalent Exceedance History at Increments of Life

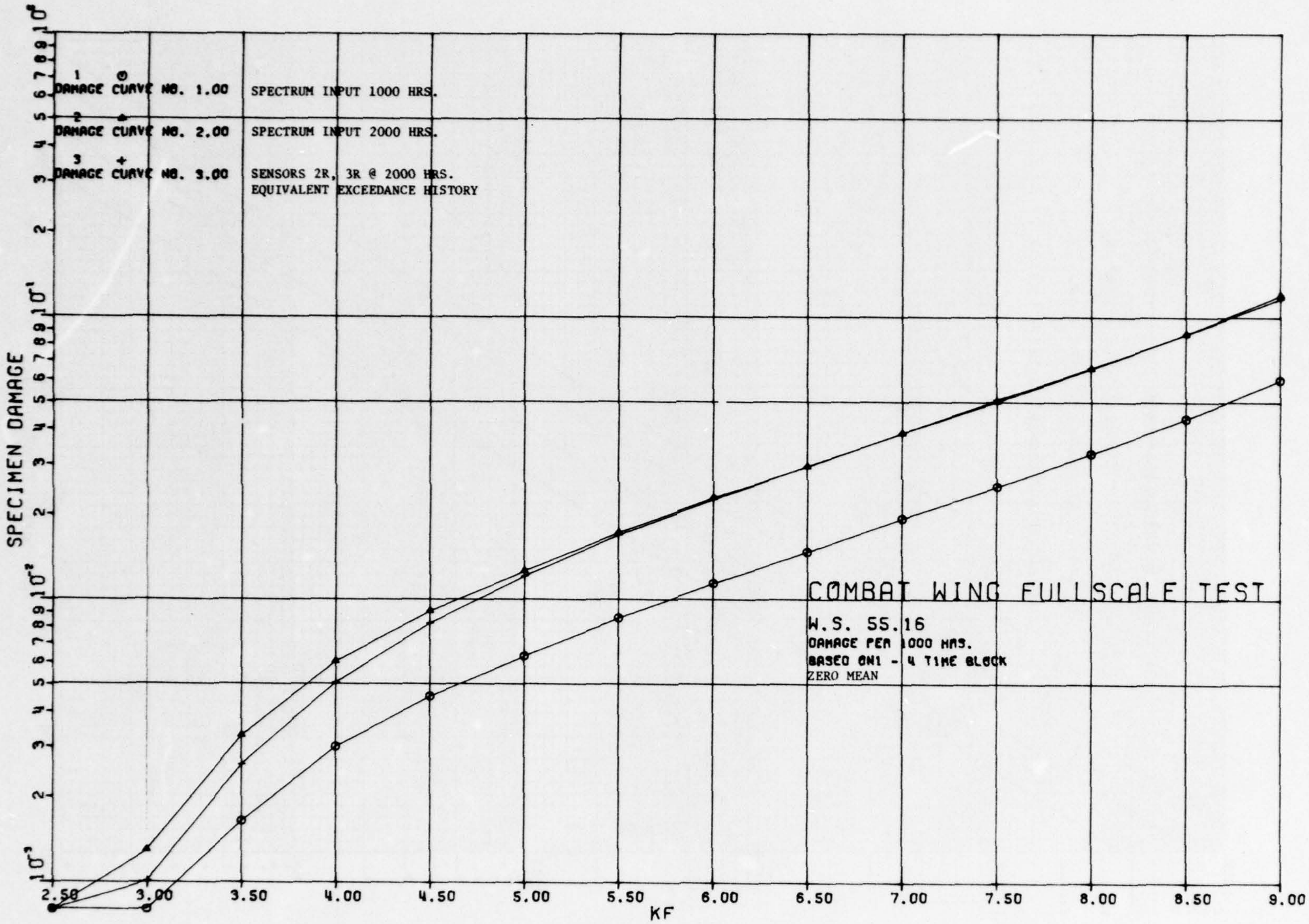

Figure 10 - Fatigue Damage at 1000 and 2000 Hours

SECTION III

MEAN STRAIN RESPONSE

A DESCRIPTION OF METHOD

In the preceeding discussion, all cyclic strain was assumed to have zero mean strain. As this is seldom the case in real life, an investigation was undertaken to account for the effect of mean strain on the fatigue damage as calculated using fatigue sensor techniques. The response of the fatigue sensor to mean strain is small and occurs only during the early life of the sensor. The fatigue sensor is less stable during its very early life making mean strain evaluation by this means subject to error, and the volume of data currently available is not adequate to fully define this small fatigue sensor response to mean strain effects. For all of these reasons it was not judged to be feasible at this time to attempt a mean strain analysis based on fatigue sensor data alone.

Therefore, an empirical method was developed based on the mean strain being equal to a fixed percentage of alternating strain for each cycle. This percentage is established experimentally for the spectrum in question. The mean strain percentage appears to remain constant for any particular type of usage such as training, combat, etc. All test cases which have been run using the available data (see Section V) have shown the method to be a usable tool.

In practice, the technique is used as follows:

1. A spectrum derived from scratch gage, Life History Recorder or test data is used to calculate a damage rate for a particular usage. Actual alternating and mean strain are used for this calculation.

2. A damage calculation is run using actual alternating strain and percentage of alternating strain as a mean strain.

3. This percentage is adjusted so that the calculated damage matches that from step 1.

4. This adjusted percentage is applied to the Equivalent Exceedance History to obtain the fatigue damage for the individual aircraft, different usage period, etc.

Fatigue sensor data taken from the Combat Wing Full Scale Test (Reference 5) is used to illustrate this technique in Figure 11. Curves 1 and 2 compare calculated damage from spectrum input (zero mean) and fatigue sensor data. Curves 3 and 4 compare this damage from spectrum input (actual mean) and fatigue sensor data using the above technique.

Reference 5. -"Final Fatigue Program", Revision F, Cessna Report 318E-6918-213, 21 February 1972.

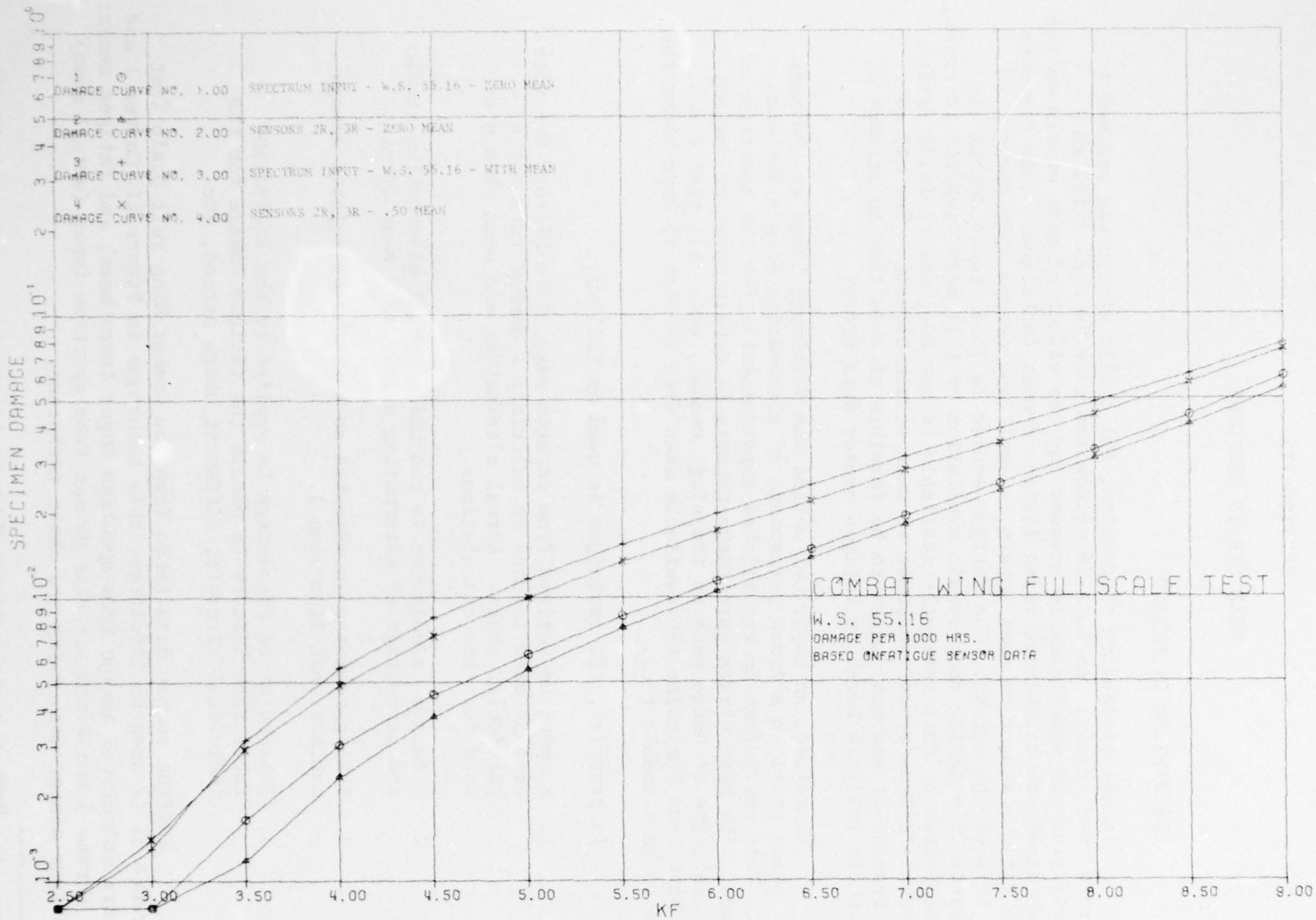

Figure 11 - Mean Strain Adjustment Example

SECTION IV

DIRECT DAMAGE METHOD

A DEVELOPMENT OF METHOD

A-1 Background

In addition to the Equivalent Exceedance History technique of Section II, it seemed desirable to have a data analysis method for monitoring individual aircraft fatigue damage which would require a less complex instrumentation installation and which would not require computer use for data analysis. While the traditional load severity comparison technique is a useful tool, it requires the use of a calibration curve from test data or a prediction curve based on a known load spectrum, both of which may be unattainable. In addition, the results are qualitative, ie, load spectrum is more severe or less severe than that of the calibration. The Direct Damage Method which was developed produces a quantitative answer directly in terms of structural fatigue damage.

The similarity of the Cycles to Fatigue Damage and Cycles to Resistance Change curves, see Figure 12, led to the belief that a matching of these curves would be possible which would yield a proportional relationship between sensor resistance change and structural fatigue damage.

A-2 Development Technique

Any number of combinations of constant amplitude alternating strain and applied cycles may be used to produce a given value of resistance change, see Figure 13.

If each of these combinations is used to calculate fatigue damage using a range of K_f values, one K_f value will be found for which all combinations produce virtually identical fatigue damage, as in Figure 14. This is taken as the "best match" of the cycles to fatigue damage and cycles to resistance change curves. If this calculation is performed for a suitable range of resistance change values for any one sensor multiplier, the results will be similar to Figure 15.

B METHOD OF APPLICATION

The application of this information may be illustrated using the data of Figures 13 through 15. The "best fit" curve for $n=4.0$, $\Delta R=1.0$ results from a K_f of 5.11 and produces a log average damage of .0021. This data Point P, is plotted on Figure 16. Also plotted on Figure 16 is a K_f versus fatigue damage curve (A-B) for a similar usage spectrum, such as may be developed using the Equivalent Exceedance History Methodology. Due to the ergodic nature of the typical strain spectra, see Figures 9 and 10, this usage

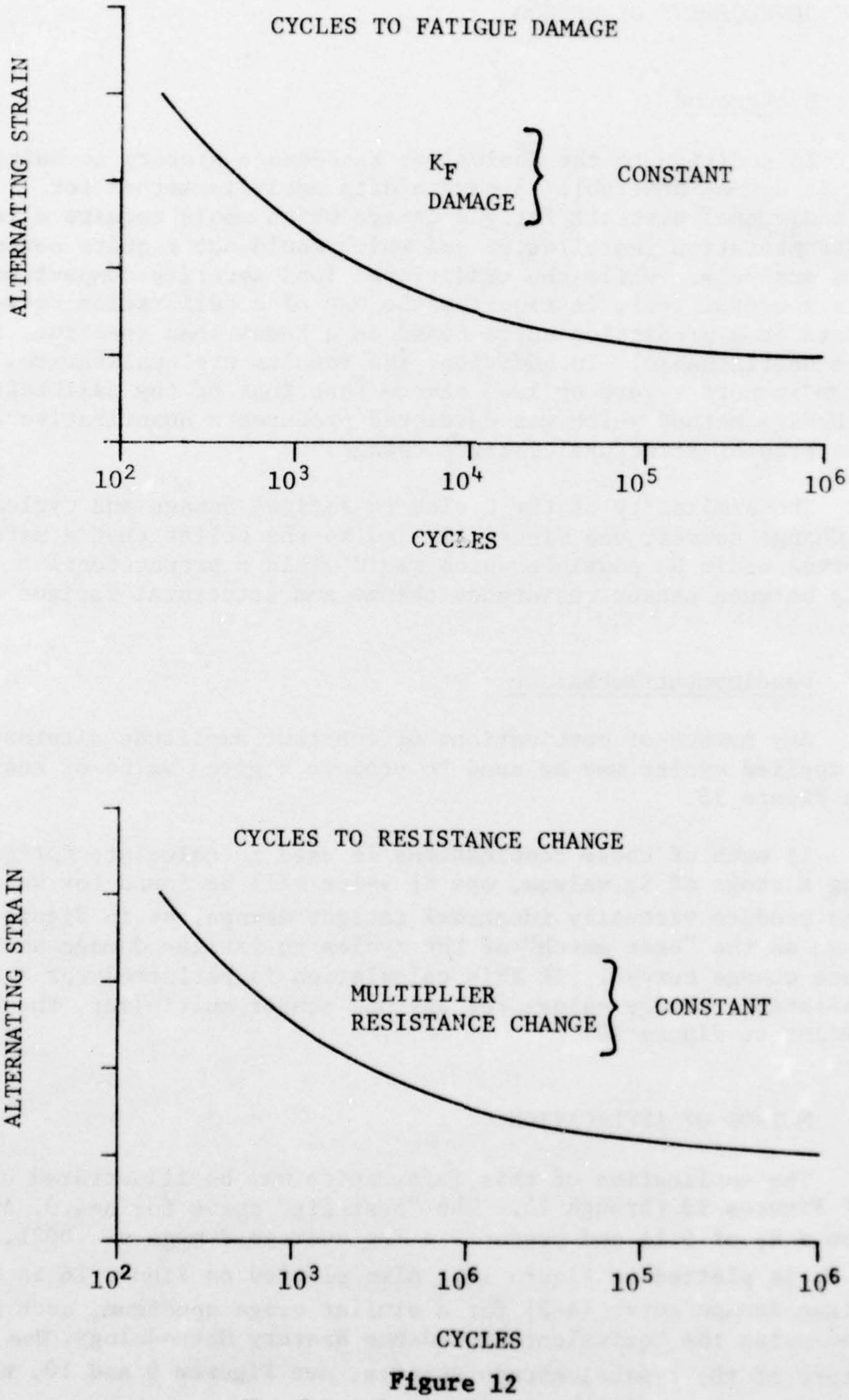

Figure 12
Matching Curve Characteristics

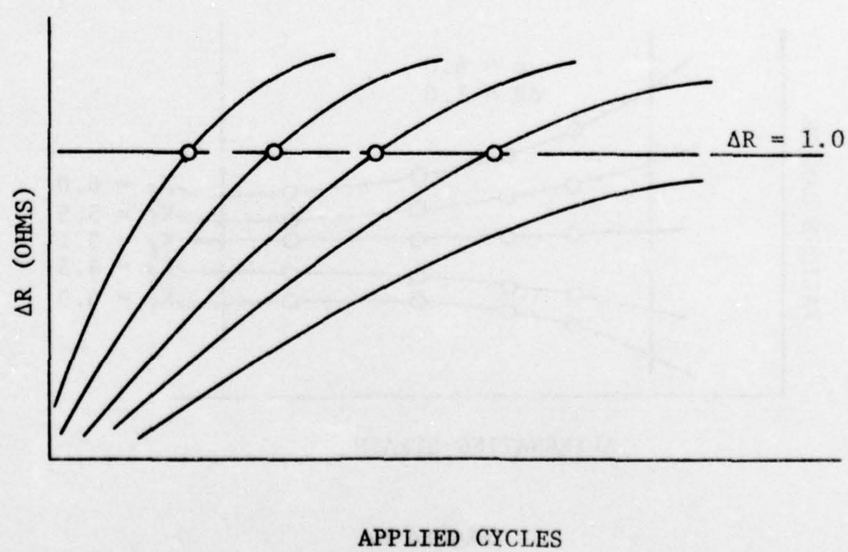

Figure 13
Constant Amplitude Strain Histories
For Constant Resistance Change

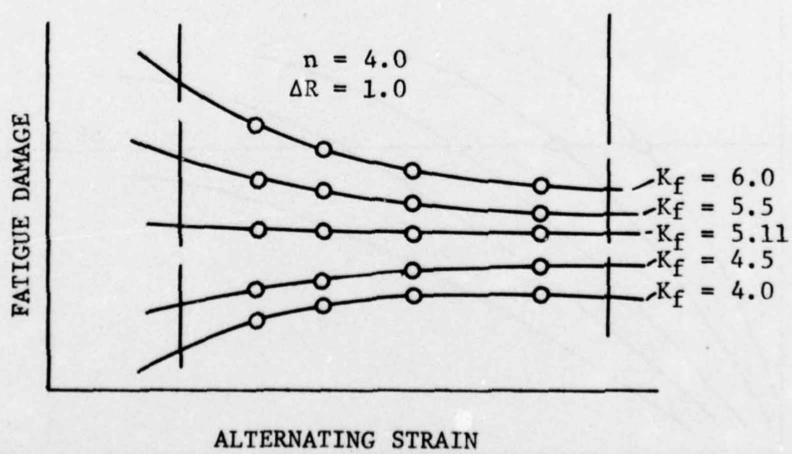

Figure 14

Constant Damage Curve For

Known Multiplier/Resistance Change Conditions

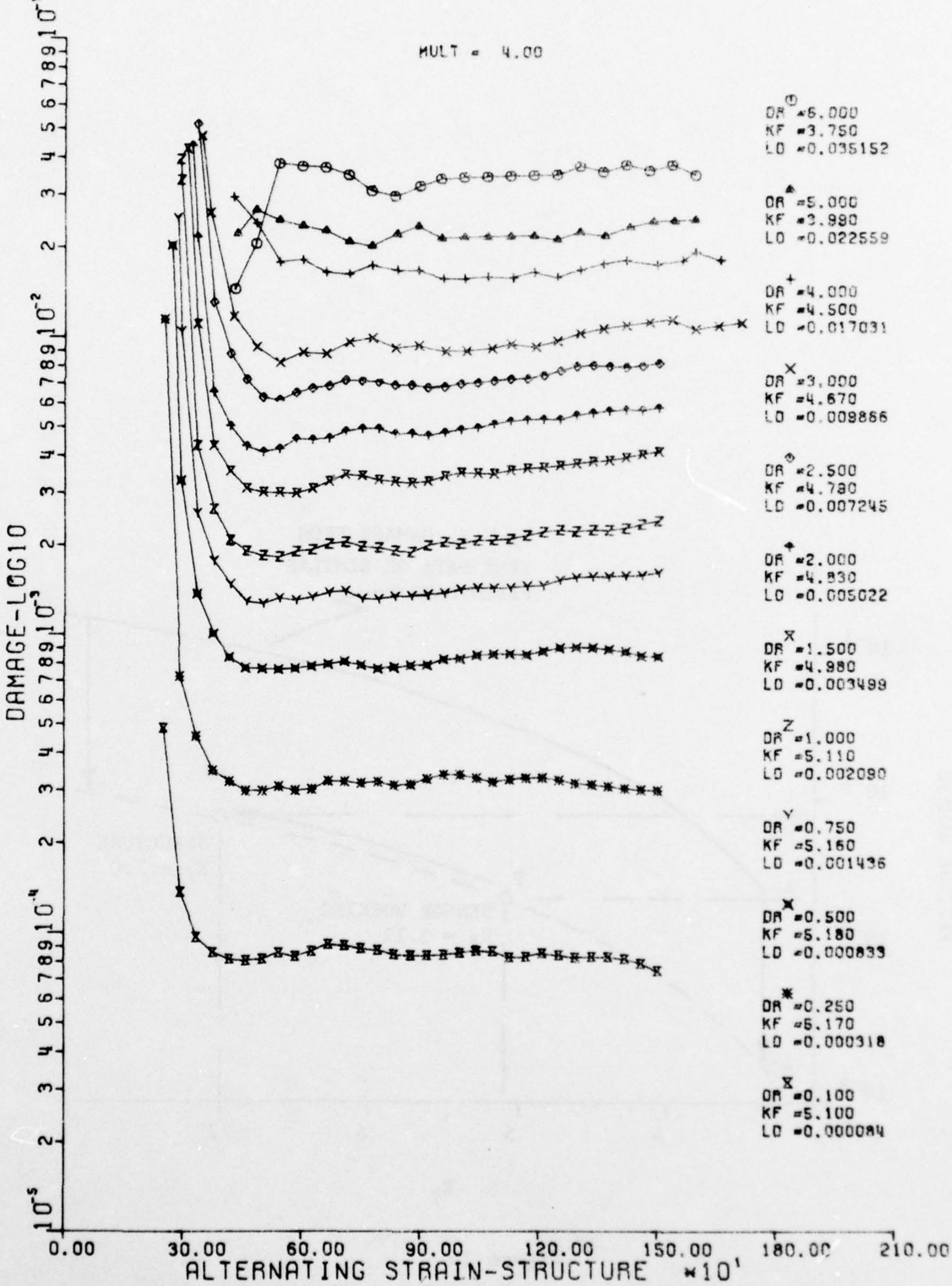

Figure 15
"Best Fit" Constant Damage Values

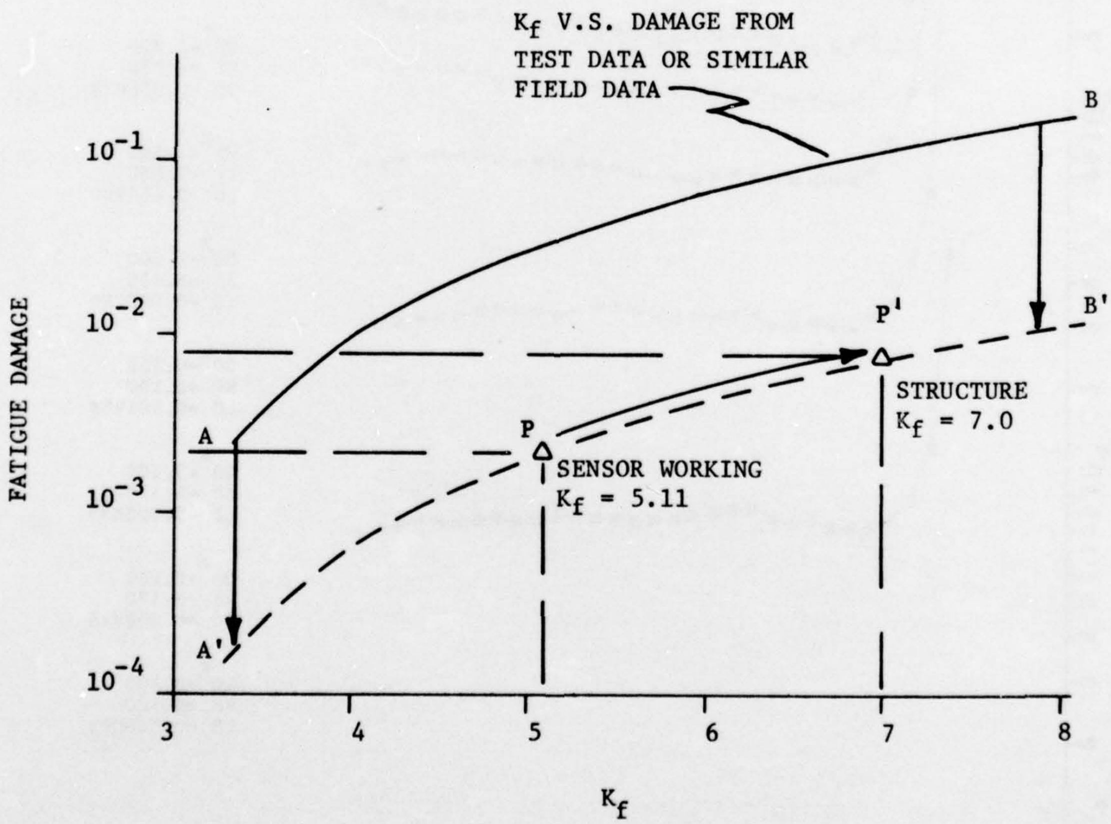

Figure 16

Damage Transfer to Structure Conditions

curve may be transferred vertically (A'-B') so that it passes through our data point.

The data Point P, is then transferred along this line (A'-B') from the sensor working K_f of 5.11 to the structure K_f of 7.0 at P'. Opposite this we read the structure fatigue damage of .008.

C DATA ANALYSIS

To form the data base of this analysis method, the "best fit" calculation was performed for a range of multipliers from 1.0 to 5.0 and a range of resistance changes from .025 ohms to 6.0 ohms. For each of these combinations up to thirty-one alternating strain/application parings were used. The search for best fit was based on K_f steps of 0.01. A log average damage figure was obtained and the "best fit" was selected by minimum deviation from this average by the least squares method. It should be noted that several data points at the low strain end of each curve were plotted, but were dropped from the averaging calculations because the alternating strain for these points is so low as to be in the "non-linear" region of sensor performance.

The results of these calculations produced a series of plots similar to Figure 15. This data was gathered into a more usable form and is presented in two graphs. Figure 17 is a representation of the direct damage versus resistance change for the commonly used values of sensor multiplier. Figure 18 gives the associated values of sensor working K_f.

Figure 19 is shown as an illustration of the application of this Data Analysis Method using Figure 11 data obtained from Wing Station 55.16, right wing of the Combat Wing Full-Scale Test. Damage points derived from individual Sensors are superimposed in the Damage V.S. K_f curves for both spectrum input and Equivalent Exceedance History. This same presentation is used in Figure 36, Section V for 1000 and 2000 hour test intervals, as an illustration of the response to be expected from an ergodic strain history. No "on purpose" sensor installations have been made to confirm this data analysis method. however what data is available indicated good correlation between this method and other computed damages.

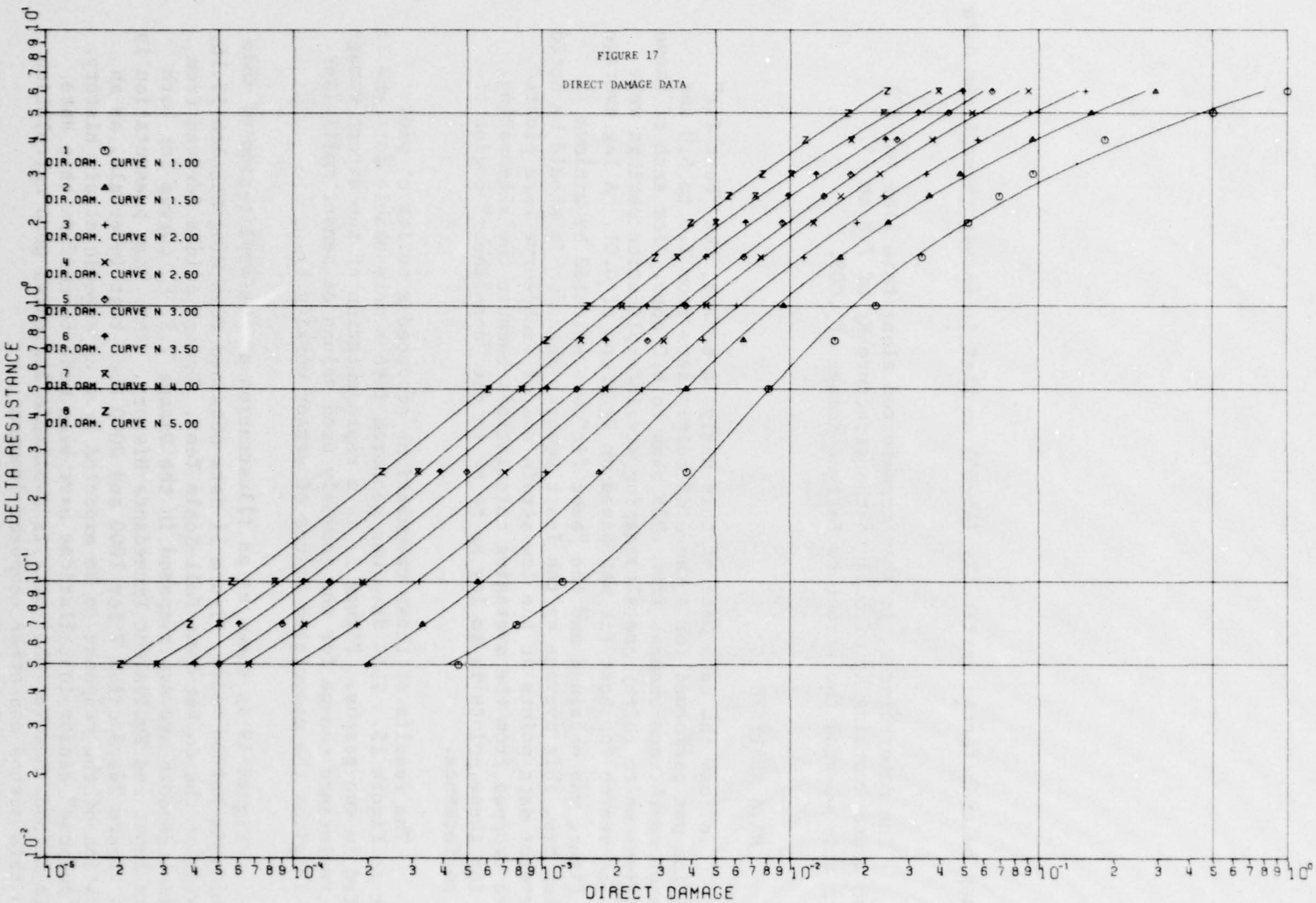

Figure 17 - Direct Damage Data

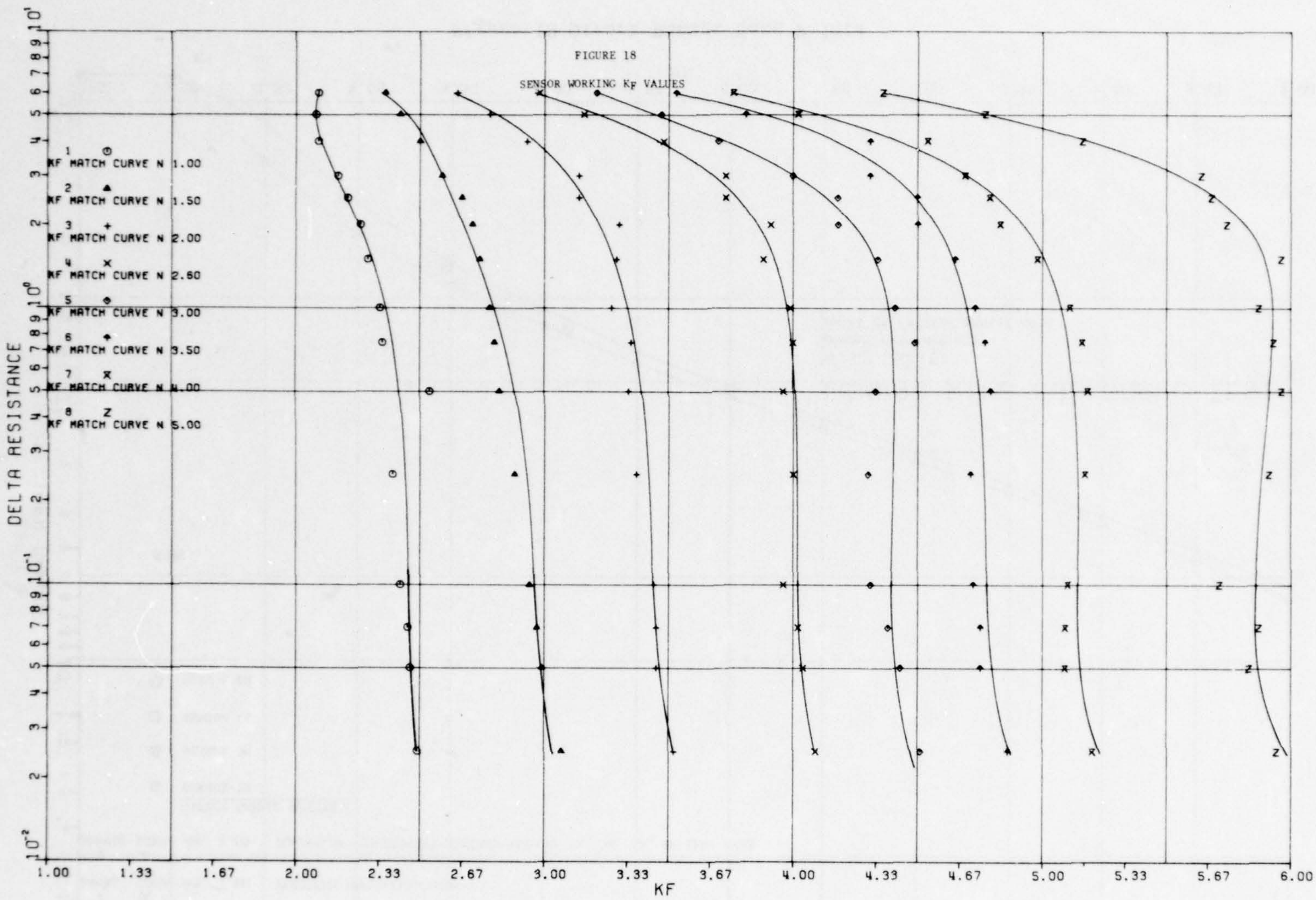

Figure 18 - Sensor Working K_f Values

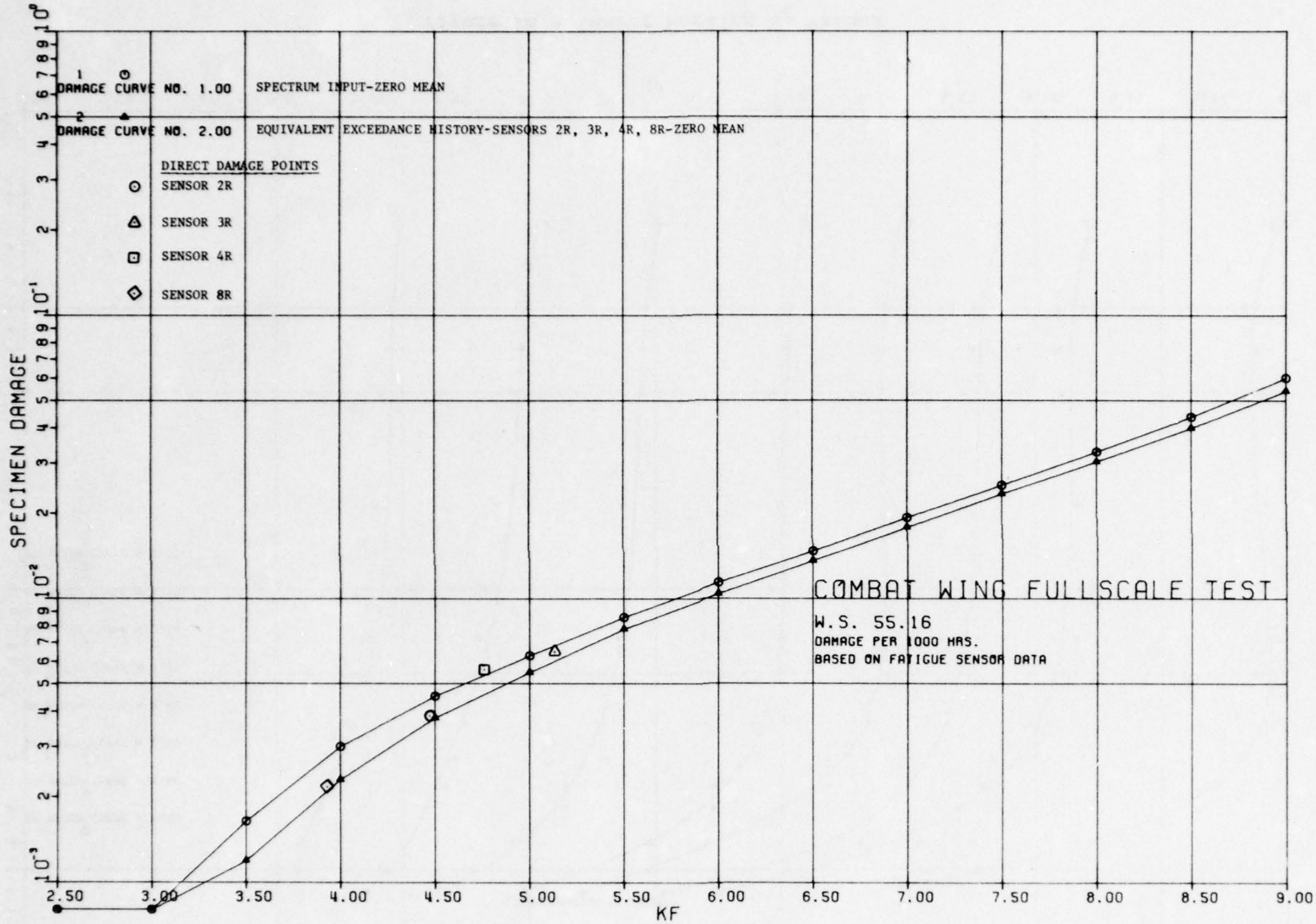

Figure 19 Direct Damage Data Points

SECTION V

SUMMARY AND RESULTS OF THE PROGRAM

A EQUIVALENT EXCEEDANCE HISTORY METHOD

A-1 Background

The Data Analysis Method investigated in Section II produces an equivalent strain history which may be used with a standard method to calculate fatigue damage. All fatigue damage calculations in this report are based on the SNK_f concept (Reference 6) using an SN curve suitable for aluminum alloys. This section of the report consists of a brief discussion of the data and its use along with comparison plots of strain exceedances and calculated damage for both the Equivalent Exceedance History and the actual load spectrum for all available usable data.

The Combat Wing Full Scale Test, Reference 5, (combat spectrum) was the first sensor installation (see Figure 20) which was made specifically for these data analysis methods and therefore, this data receives the major emphasis in this report. The fatigue sensor response data from this test is given in Table 1, Page 33, and is also shown graphically in Figure 21. The test spectrum was such that each complete time block consisted of 674 flights and was equivalent to 801.5 flight hours. Two additional flights were inserted between the first and second time blocks for calibration. The effective multipliers used in this analysis were derived from strain gage readings which were taken at that time. Strain gages were mounted adjacent to each fatigue sensor for this purpose. All Equivalent Exceedance Histories were calculated on the basis of complete time blocks and the Emax value as shown on the exceedance curve has been adjusted by the following relationship.

$$\frac{1000}{801.5} = 1.248$$

$$\frac{\log 1.248}{\log 10.0} = .0962$$

$$Emax_{1000} = Emax_{801} + .0962\ H$$

Reference 6. - Abbott, R.A., Cessna Aircraft Company, "The SNK_f Concept - A Method of SN Data Development for Aluminum Aircraft Structures", SAE Paper 740386, 2 April 1974.

The input spectrum exceedance curve and calculated fatigue damage were based on the applied test spectrum which was subjected to a range pair type cycle count, Reference 7 and 8.

The data from the Final Full Scale Fatigue Test (training spectrum) was taken from three fatigue sensors covering an effective multiplier range of 2.5 to 4.0. As a point of interest, the data of two of the gages is from gages of different multiplier values mounted in the same identical location over different time periods. All effective multipliers for this data were calculated using a stasistical average multiplier and a calculated strain transfer function. The resistance change values are taken from Table 2-2, Reference 9 for locations 2 and 3.

The England Air Force Base data (training spectrum) which is included is a composite average taken from Micro-Measurement FM Fatigue Sensors and from Dentronics Sensors[a] which were read over a previous time period. The FM Sensor multiplier was taken from the statistical average and the multiplier for the Dentronics was estimated. The resistance change data was taken from Figure 3-16 Reference 9 and Figure 4-20 through 4-22. Reference 2, and in both cases was extrapolated to obtain a ΔR value at 1000 hours.

A-2 Exceedance History Data

The Equivalent Exceedance Histories for the Combat Wing Test as calculated by this method are shown in Figures 22, 24, 26, and 28. The actual spectrum exceedance curve is shown for comparison. The fatigue damage vs. K_f curves associated with these Exceedance Histories are shown in Figures 23, 25, 27 and 29. In each case, another sensor is paired with sensor three to obtain the maximum multiplier ratio. For sensor 3L the reading at the end of the first time block was the last reading before sensor failure and the sensor was probably in the process of failure at the time of this reading. In spite of any inaccuracies introduced by this, the damage rates obtained from the left wing are well within the useful range for fatigue work. The data from the right wing produces consistantly better results.

Reference 7. - de Jonge, J.B. "The Monitoring of Fatigue Loads", National Aerospace Laboratory NLR, MP70010U.

Reference 8. - Tischler, V.A., "A Computer Program for Counting Load Spectrum Cycles Based on the Range Pair Cycle Counting Method", TM-FBR-72-4, Air Force Flight Dynamics Laboratory, Dayton, Ohio, November 1972.

Reference 9. - "Fatigue Sensor Evaluation Program - Interim Full Scale Fatigue Test Field Aircraft Instrumentation Report", Cessna Report 318E-7419-039.

[a]Dentronics Sensor - Type SAP204 Fatigue Sensor Manufactured by Dentronics Inc., Hackensack, New Jersey.

The damage rates calculated from the Fatigue Sensor data from the Final Full Scale Fatigue Test are shown in Figure 30. As previously noted, this was not an "on purpose" installation for these Data Analysis Methods and the data was collected over two widely separated time periods. Even so, the maximum error in calculated damage is approximately 20 percent and this is at the low K_f (low damage rate) end of the range.

The field data from England Air Force Base was used to calculate the damage rates shown in Figure 31. This data, representing as it does, two different makes of sensor, one of them not load compensated, and taken over different time periods as well as from different aircraft, is about as 'shaky' as data can get. None the less, the maximum error of approximately 25% over the K_f range of 5.0 to 9.0 would certainly be useful if no other data existed.

B MEAN STRAIN RESPONSE

The mean strain techniques outlined in Section III were applied to the damage data included in this report. The mean strain percentages of .66 for the training spectrum and .50 for the combat spectrum were obtained experimentally. It should be noted that these values are in line with the relative severity of mean strain for these usages. For each data case presented, the Input Spectrum and Equivalent Exceedance History curves at zero mean strain should be used as a model for comparison with the Input Spectrum-with Mean/Equivalent Exceedance History-Percent Mean pair of curves. In every case, the percent mean strain technique has shown an acceptable degree of accuracy in accounting for the effects of mean strain. The results of the mean strain investigation for the Combat Wing Full Scale Test are shown in Figures 32 through 34. The mean strain results for the Final Full Scale Fatigue Test and the England AFB Field Data are shown with the zero mean strain results in Figures 30 and 31. As a measure of the sensitivity of the method to accurate selection of the percentage of alternating to be used as mean strain, Figure 35 presents the damage rates for .40 and .60 mean strain as well as the optimum .50, all based on Combat Wing Test Data.

C DIRECT DAMAGE

The Direct Damage Techniques developed in Section IV have been applied to the same data which was examined by the Equivalent Exceedance History Method. For the Combat Wing Full Scale Fatigue Test Spectrum, 1000 flight hours was equivalent to approximately 840 flights. The resistance change data for 1000 hours was obtained by interpolation between the values in Table 1 for 800 and 900 flights. For data at approximately 2000 hours, the reading after 1750 flights was used which is equivalent to 2080 hours. The damage points for 1000 and 2080 hours are shown on Figure 36, along with the damage curves derived from the input spectrum at 1000 and 2000 hours.

The data used from the Final Full Scale Test and from England AFB is the same data used in the Exceedance Curve Method. This data is presented in Figure 37 and 38.

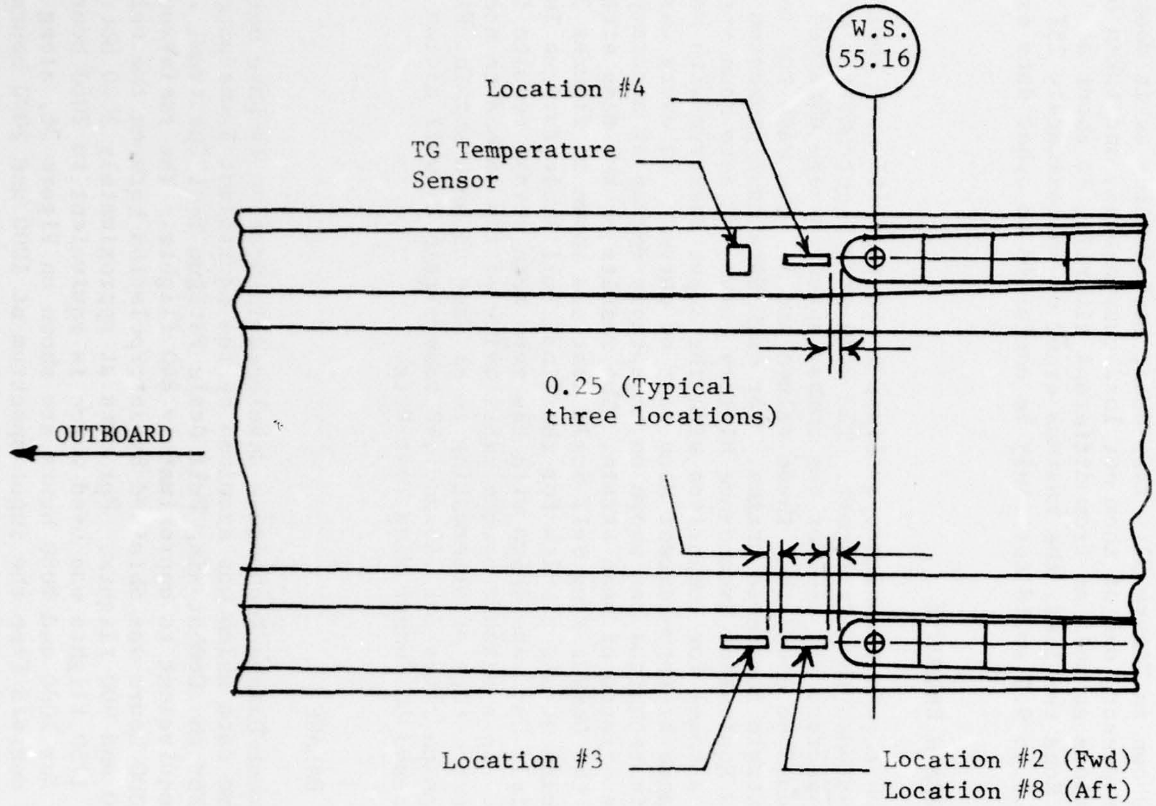

Figure 20 - Sensor Location - Combat Wing Full Scale Fatigue Test

RESISTANCE CHANGE DATA -- COMBAT WING TEST

TABLE 1

ZERO TEMP.= 77.1

	2R	2L	3R	3L	4R	4L	5R	5L	6R	6L	8R	8L	9R	9L
MULTIPLIER	2.5	2.5	4.0	4.0	3.5	3.5	3.0	3.0	5.0	5.0	2.0	2.0	4.0	4.0
INTIAL ZERO READING	0.353	0.025	0.280	-0.073	0.080	0.353	0.601	0.300	0.467	-0.208	-0.255	-0.500	-0.048	0.118

CALCULATED VALUES OF DELTA R

RD	FLTS	TEMP	2R	2L	3R	3L	4R	4L	5R	5L	6R	6L	8R	8L	9R	9L
1.	1.	78.3	0.012	0.013	0.022	0.023	0.015	0.014	0.026	0.025	0.037	0.010	0.010	0.010	0.033	0.034
2.	2.	78.7	0.017	0.018	0.032	0.034	0.025	0.023	0.035	0.033	0.061	0.047	0.010	0.010	0.049	0.049
3.	3.	79.0	0.023	0.023	0.043	0.046	0.032	0.031	0.045	0.044	0.082	0.068	0.010	0.011	0.063	0.067
4.	5.	79.4	0.029	0.031	0.057	0.064	0.049	0.042	0.058	0.058	0.113	0.098	0.010	0.014	0.088	0.092
5.	7.	80.2	0.037	0.039	0.074	0.080	0.061	0.055	0.073	0.074	0.146	0.130	0.013	0.020	0.114	0.120
7.	15.	82.3	0.071	0.072	0.145	0.164	0.120	0.106	0.135	0.133	0.305	0.279	0.018	0.037	0.227	0.241
8.	25.	84.0	0.095	0.095	0.197	0.222	0.160	0.139	0.172	0.173	0.390	0.368	0.032	0.047	0.297	0.313
9.	50.	86.4	0.143	0.145	0.310	0.350	0.243	0.209	0.248	0.252	0.581	0.569	0.059	0.070	0.456	0.475
10.	100.	82.0	0.227	0.231	0.510	0.565	0.388	0.328	0.378	0.389	0.909	0.912	0.097	0.112	0.725	0.751
11.	150.	86.5	0.294	0.300	0.682	0.749	0.503	0.429	0.486	0.506	1.193	1.206	0.125	0.145	0.963	0.989
12.	200.	88.5	0.359	0.368	0.839	0.918	0.612	0.524	0.587	0.614	1.441	1.467	0.156	0.177	1.173	1.200
13.	300.	92.0	0.542	0.554	1.223	1.335	0.882	0.778	0.899	0.942	2.127	2.126	0.247	0.279	1.746	1.755
14.	400.	85.0	0.655	0.668	1.464	1.602	1.067	0.944	1.088	1.149	2.516	2.511	0.297	0.336	2.086	2.102
15.	500.	111.0	0.756	0.774	1.694	1.863	1.210	1.082	1.241	1.315	2.831	2.816	0.341	0.385	2.383	2.397
16.	674.	80.6	1.008	1.035	2.187	2.417	1.596	1.444	1.648	1.747	3.614	3.665	0.464	0.516	10.000	3.095
16.A	677.	80.8	1.017	1.040	2.199	10.000	1.613	1.477	1.656	1.760	3.686	3.762	0.475	0.525	10.000	3.111
17.	700.	81.9	1.049	1.075	2.255	10.000	1.612	1.476	1.702	1.806	3.702	3.788	0.492	0.544	10.000	3.185
18.	800.	82.0	1.127	1.157	2.397	10.000	1.726	1.585	1.807	1.922	3.972	4.130	0.527	0.583	10.000	3.402
19.	900.	79.0	1.191	1.225	2.514	10.000	1.827	1.682	1.892	2.020	4.251	4.437	0.558	0.619	10.000	3.580
20.	1000.	83.0	1.296	1.336	2.715	10.000	1.974	1.829	2.057	2.199	4.692	4.885	0.615	0.678	10.000	3.896
21.	1100.	80.6	1.343	1.386	2.815	10.000	2.039	1.897	2.135	2.283	4.900	5.109	0.636	0.703	10.000	4.064
22.	1200.	85.5	1.442	1.490	3.061	10.000	2.159	2.018	2.265	2.423	5.317	5.495	0.687	0.757	10.000	4.377
23.	1350.	81.6	1.580	1.630	3.307	10.000	2.360	2.225	2.470	2.637	6.899	6.761	0.757	0.833	10.000	4.882
24.	1500.	80.2	1.672	1.721	3.485	10.000	2.446	2.326	2.574	2.741	10.000	10.000	0.804	0.882	10.000	5.237
25.	1750.	78.7	1.816	1.864	3.842	10.000	2.639	2.531	2.779	2.953	10.000	10.000	0.879	0.963	10.000	6.062
27.	2024.	83.6	1.994	2.042	4.395	10.000	2.889	2.795	3.024	3.204	10.000	10.000	0.978	1.067	10.000	10.000
28.	2200.	83.8	2.063	2.113	4.640	10.000	2.963	2.879	3.116	3.289	10.000	10.000	1.016	1.107	10.000	10.000
29.	2400.	82.7	2.165	2.201	10.000	10.000	3.133	3.050	3.263	3.431	10.000	10.000	1.075	1.167	10.000	10.000
30.	2600.	80.3	2.291	2.313	10.000	10.000	3.273	3.194	3.443	3.616	10.000	10.000	1.142	1.237	10.000	10.000
31.	2698.	83.4	2.321	2.356	10.000	10.000	3.355	3.300	3.483	3.674	10.000	10.000	1.159	1.256	10.000	10.000
32.	2698.	83.6	2.325	2.364	10.000	10.000	3.365	3.282	3.498	3.689	10.000	10.000	10.000	1.258	10.000	10.000
44.	2898.	85.3	2.392	2.423	10.000	10.000	3.477	3.397	3.569	3.760	10.000	10.000	10.000	1.281	10.000	10.000
46.	3098.	87.0	2.493	2.509	10.000	10.000	3.619	3.529	3.716	3.919	10.000	10.000	10.000	1.330	10.000	10.000
48.	3372.	84.0	2.682	2.664	10.000	10.000	3.942	3.807	3.996	4.230	10.000	10.000	10.000	1.416	10.000	10.000
51.	3598.	82.4	2.781	2.749	10.000	10.000	4.207	4.012	4.174	4.439	10.000	10.000	10.000	1.454	10.000	10.000
53.	3798.	85.7	2.857	2.805	10.000	10.000	4.530	4.161	4.333	4.711	10.000	10.000	10.000	1.478	10.000	10.000
55.	4046.	87.4	2.988	2.907	10.000	10.000	5.101	4.430	4.659	5.070	10.000	10.000	10.000	1.543	10.000	10.000
57.	4448.	87.0	3.153	3.017	10.000	10.000	10.000	4.912	5.106	5.540	10.000	10.000	10.000	1.607	10.000	10.000
59.	4720.	90.2	3.279	3.104	10.000	10.000	10.000	5.297	5.711	6.189	10.000	10.000	10.000	1.656	10.000	10.000
63.	5394.	81.4	3.593	3.338	10.000	10.000	10.000	7.732	7.634	10.000	10.000	10.000	10.000	1.778	10.000	10.000
64.	6068.	81.4	4.005	3.607	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000	1.888	10.000	10.000

NOTE-- CALCULATED VALUES OF DELTA R HAVE NOT BEEN CORRECTED TO THE ZERO TEMPERATUE

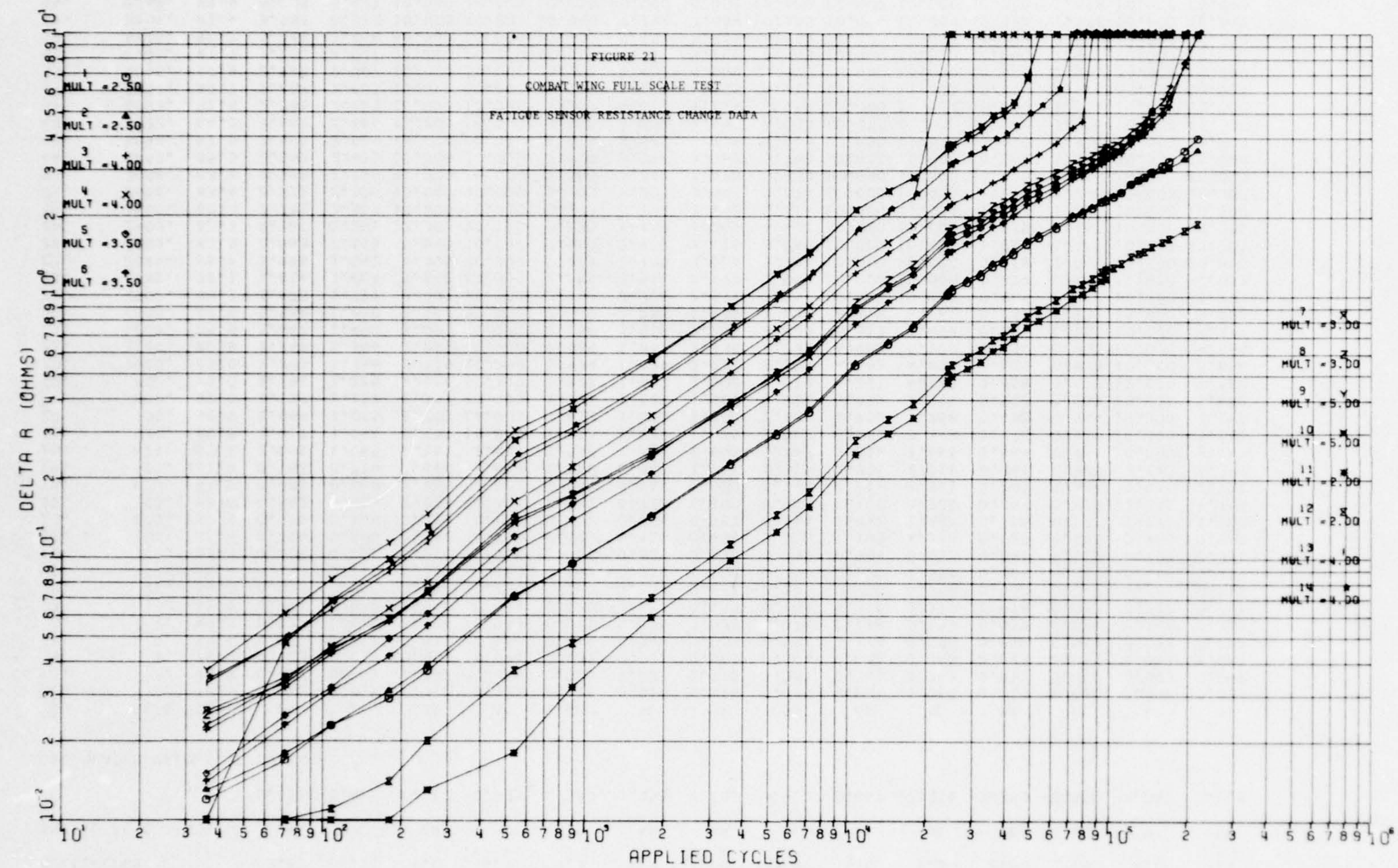

Figure 21 - Combat Wing Test - Fatigue Sensor Resistance Change Data

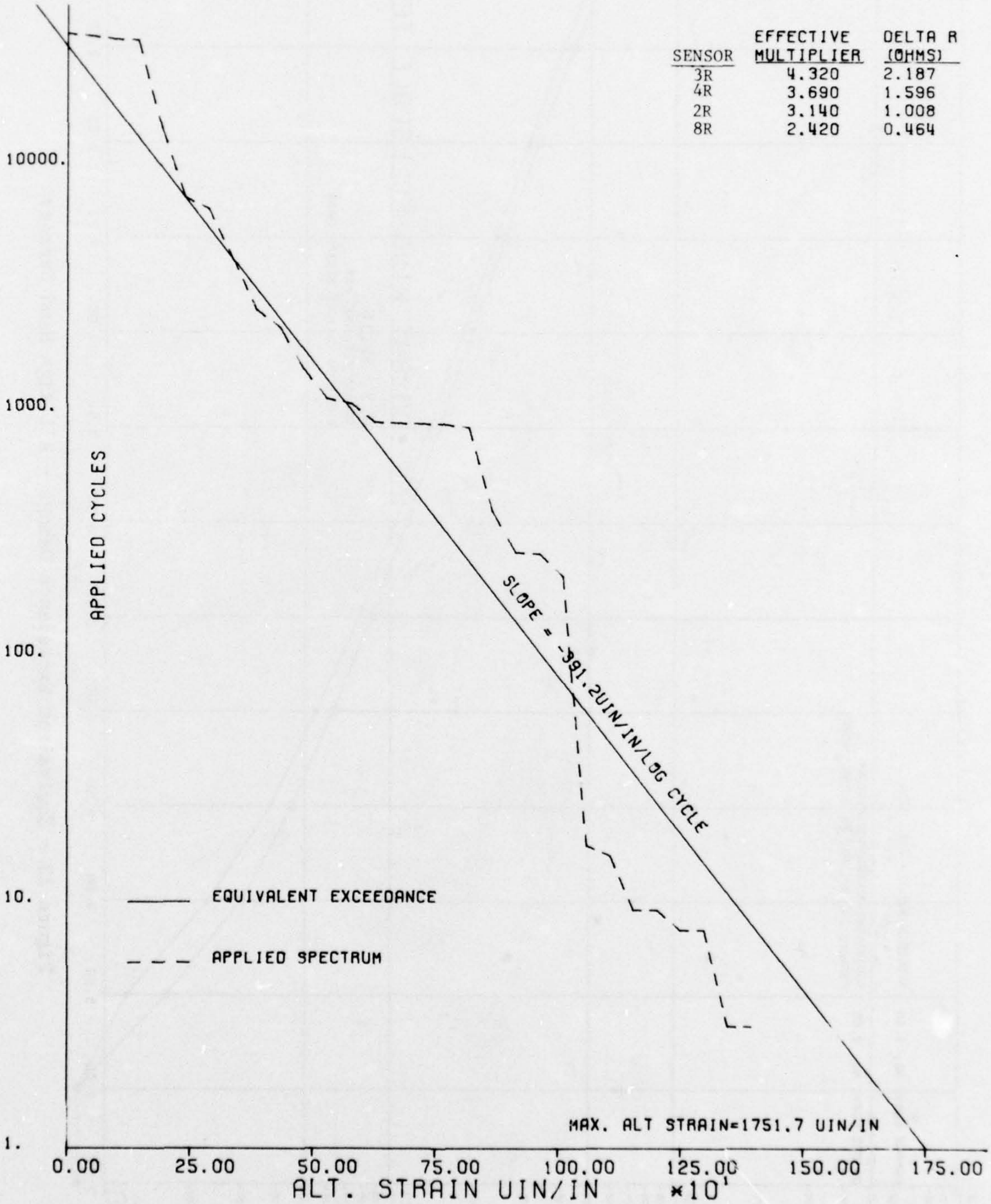

Figure 22 Equivalent Exceedance History - Combat Wing Test All Right Hand Sensors

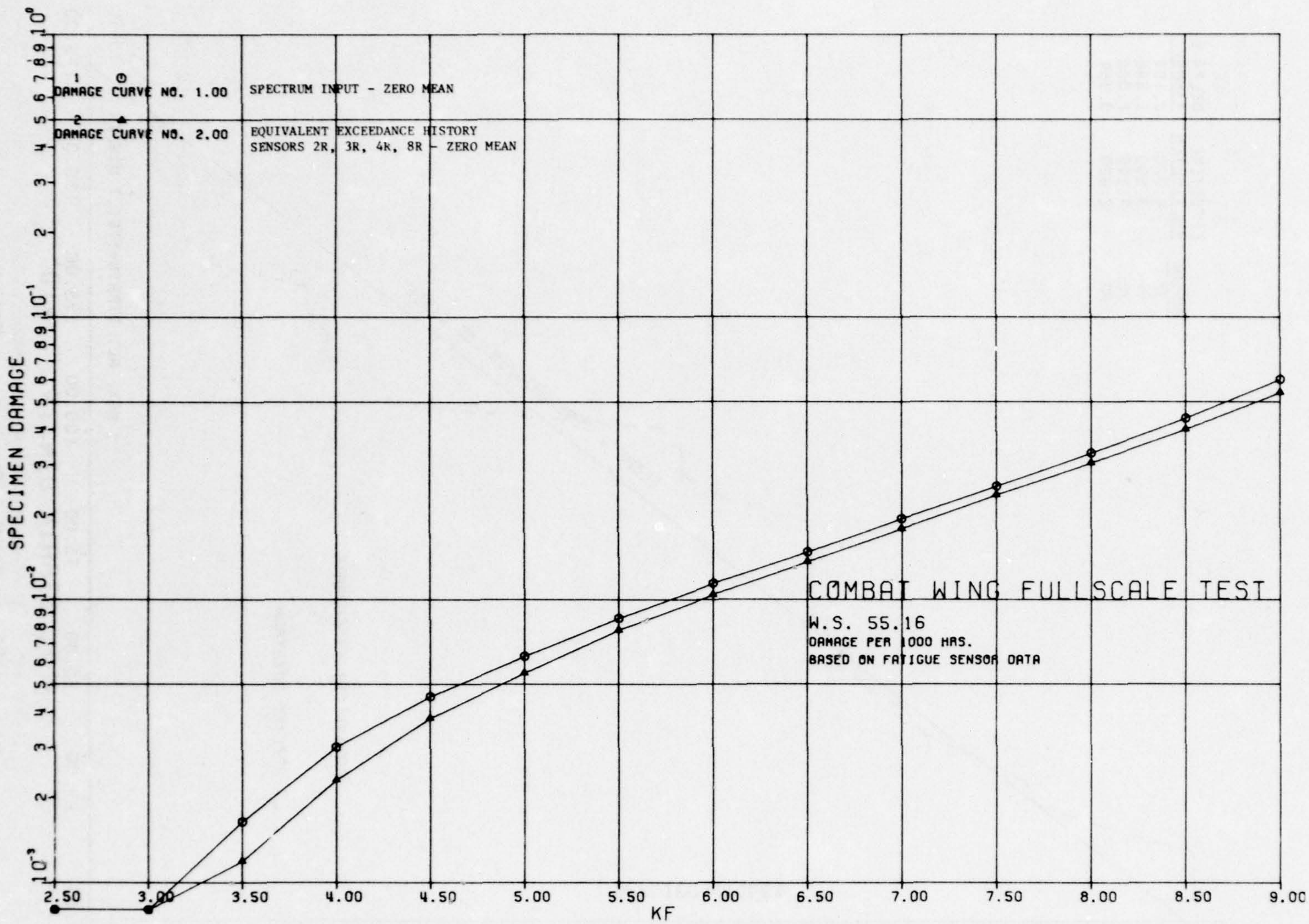

Figure 23 - Equivalent Exceedance Damage - All Righ Hand Sensors

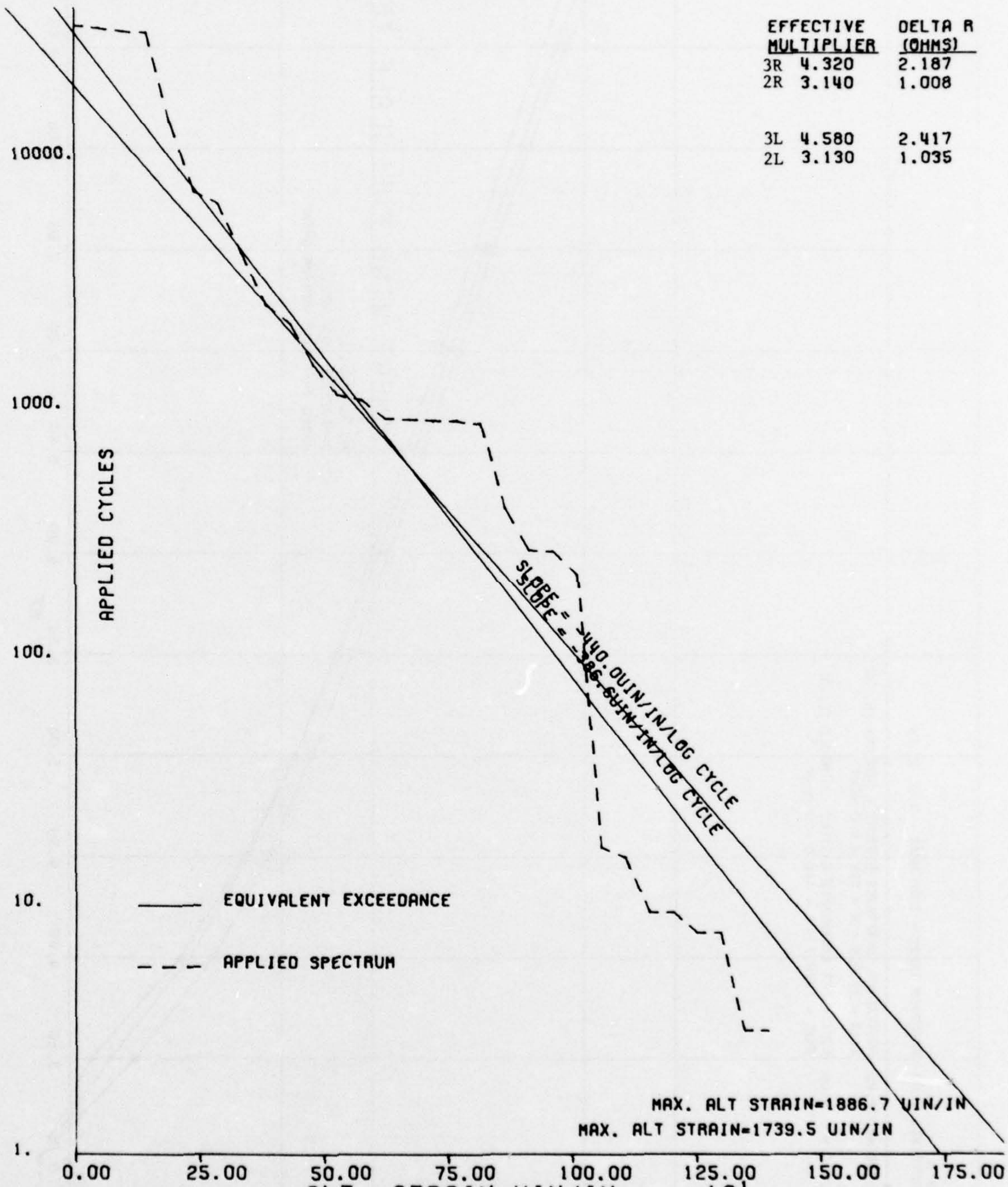

Figure 24
Equivalent Exceedance History - Combat Wing
Test Sensors 2 and 3 - Right and Left

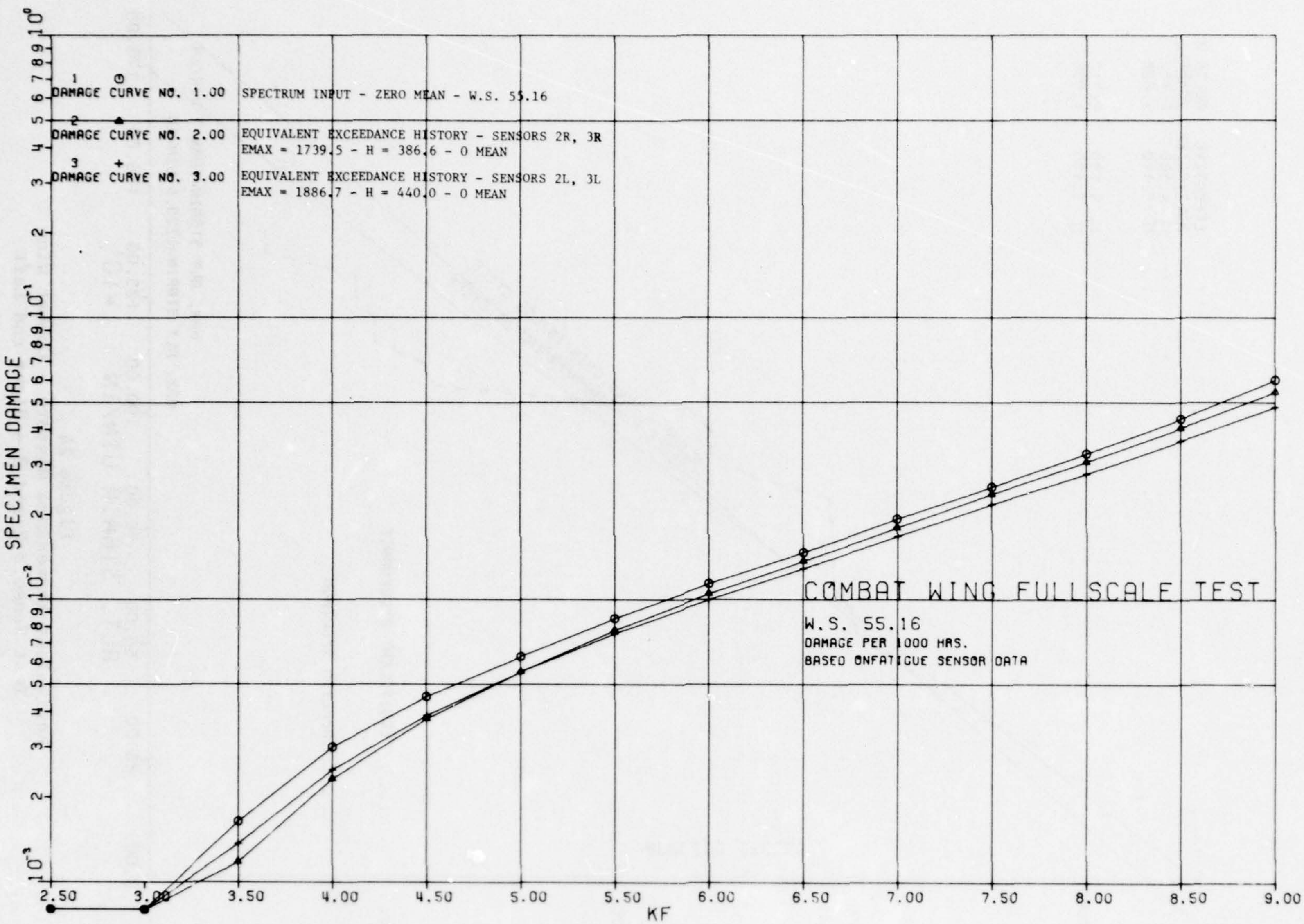

Figure 25 - Equivalent Exceedance Damage - Sensors 2 and 3

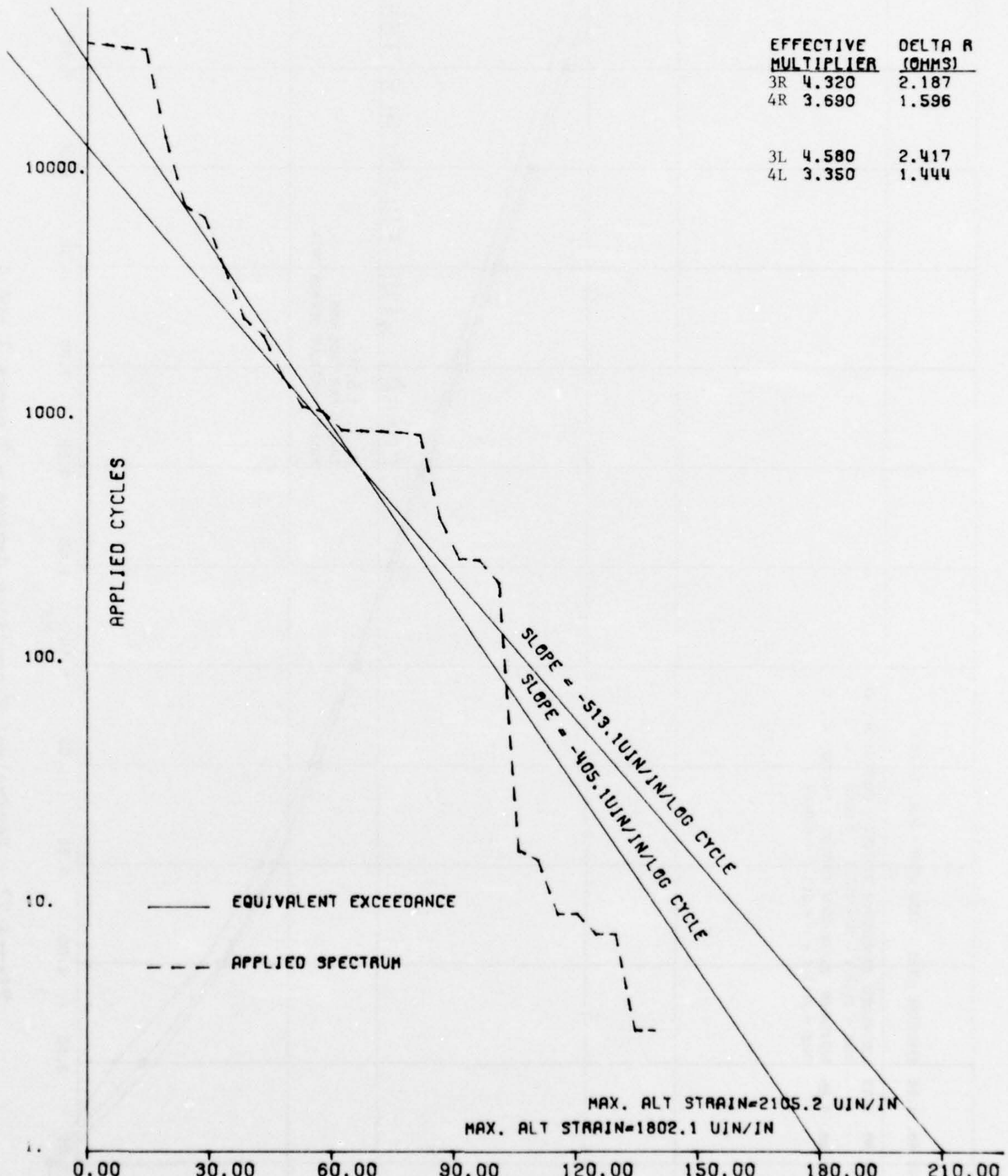

Figure 26
Equivalent Exceedance History - Combat Wing
Test Sensors 3 and 4 - Right and Left

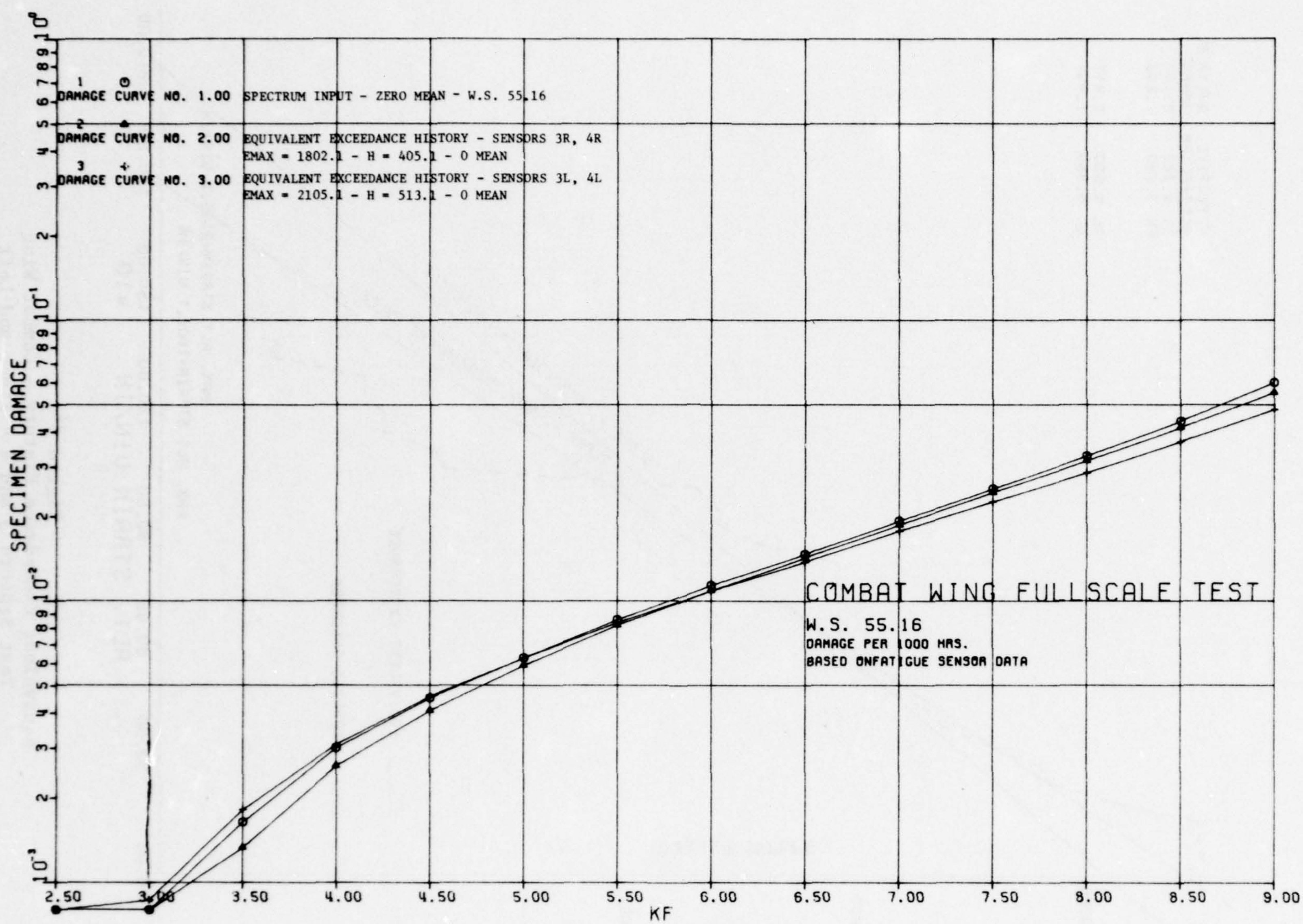

Figure 27 - Equivalent Exceedance Damage - Sensors 3 and 4

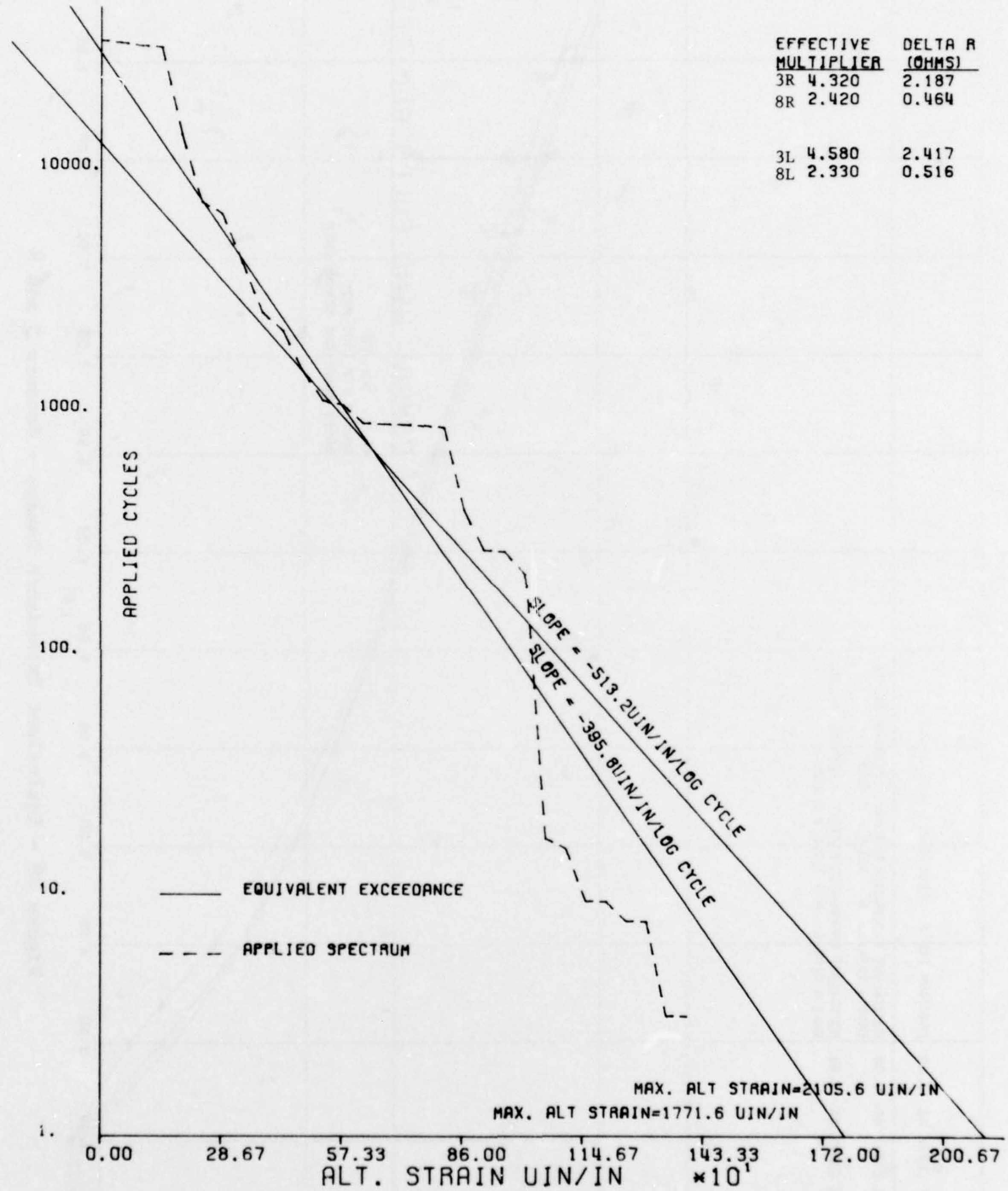

Figure 28
Equivalent Exceedance History - Combat Wing
Test Sensors 3 and 8 - Right and Left

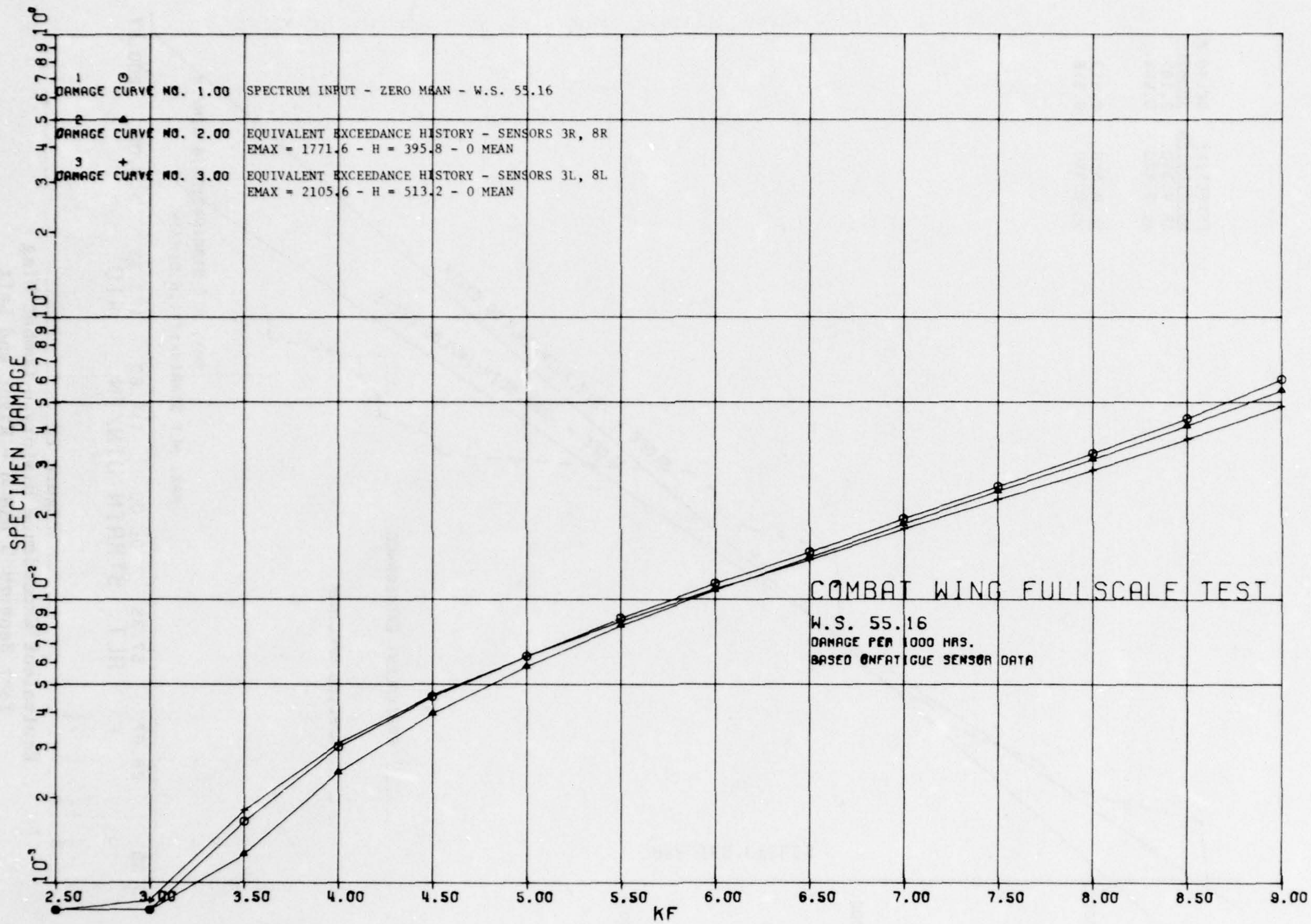

Figure 29 - Equivalent Exceedance Damage - Sensors 3 and 8

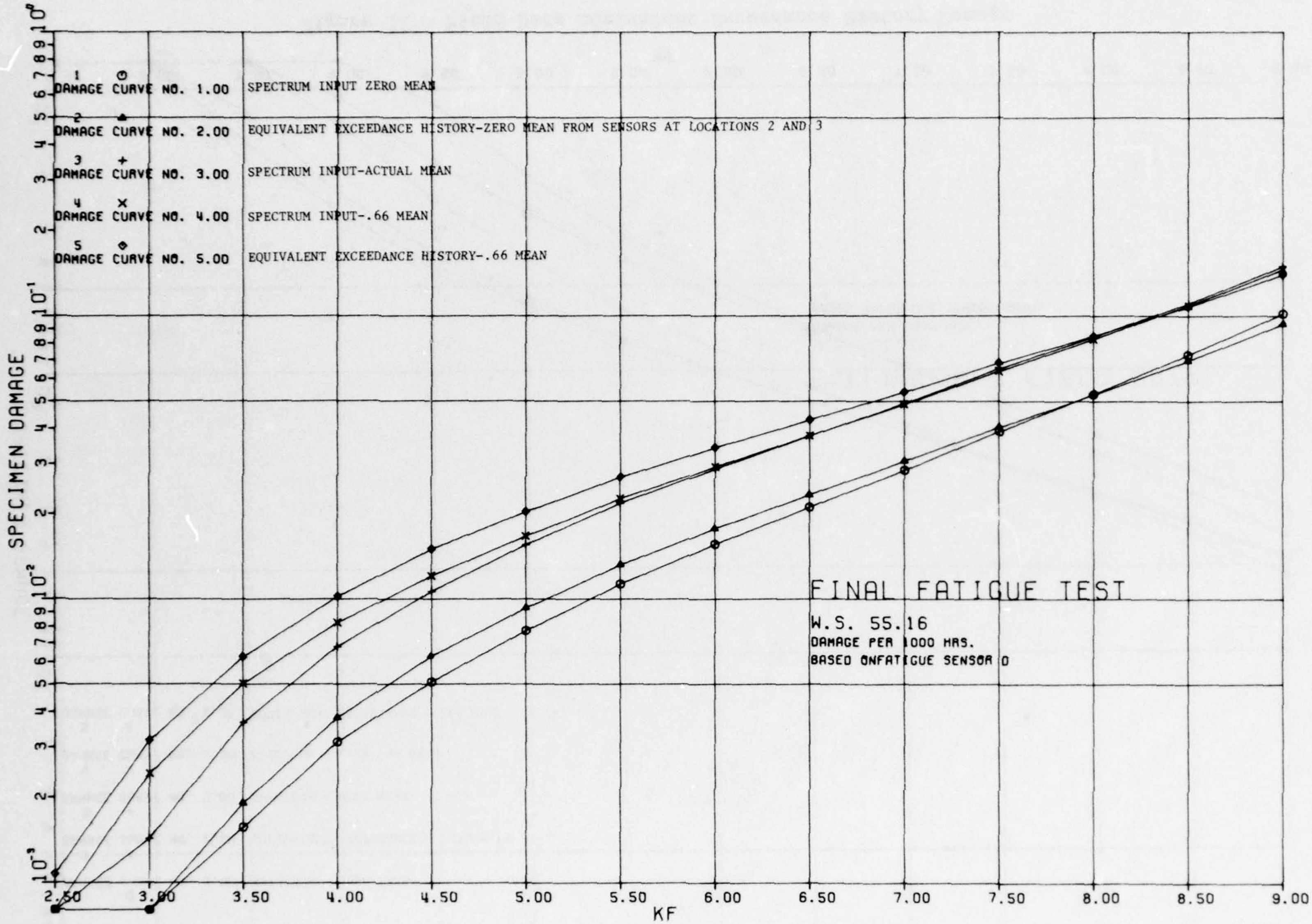

Figure 30 - Equivalent Exceedance History Damage - Final Fatigue Test

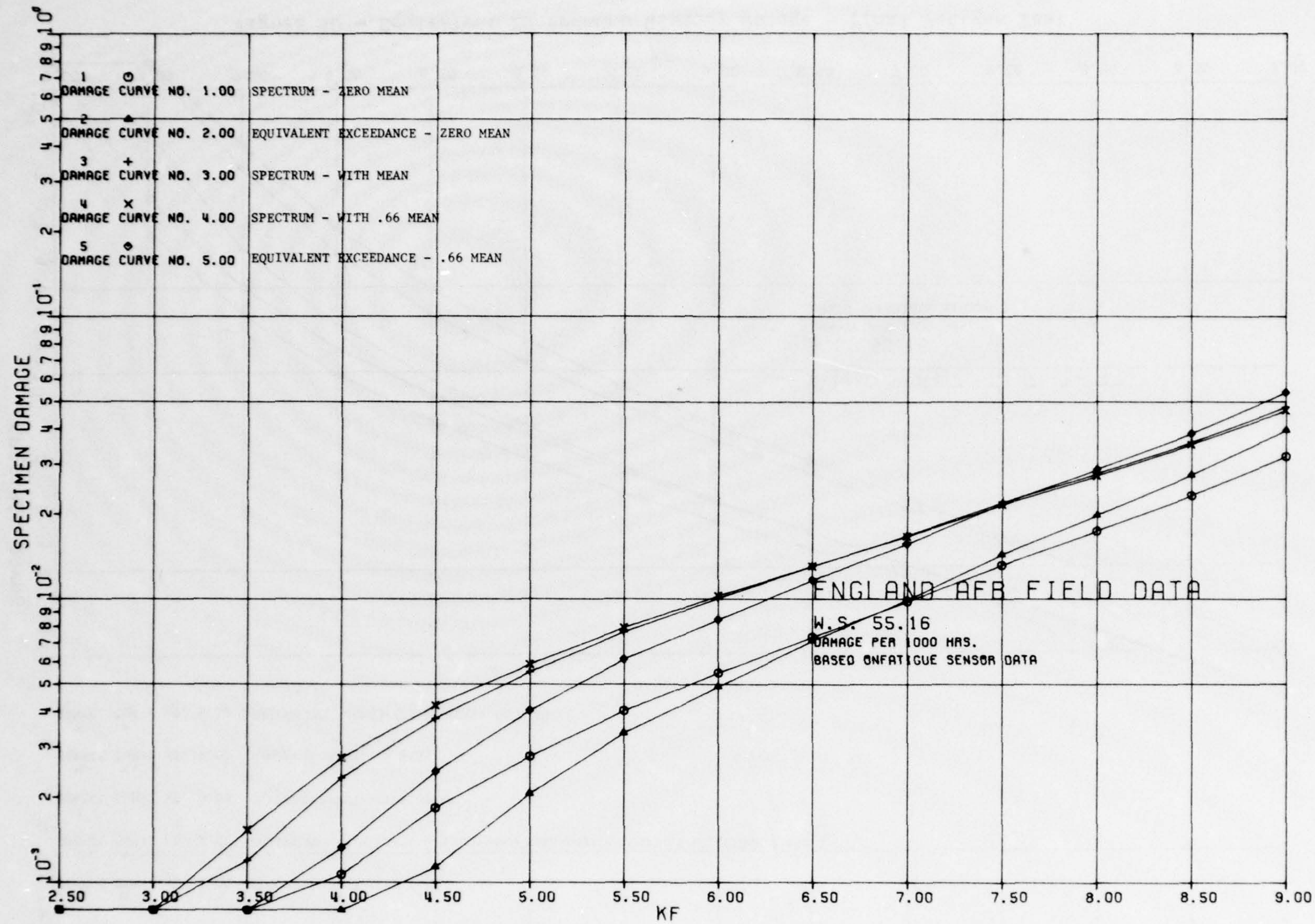

Figure 31 - Field Data Equivalent Exceedance History Damage

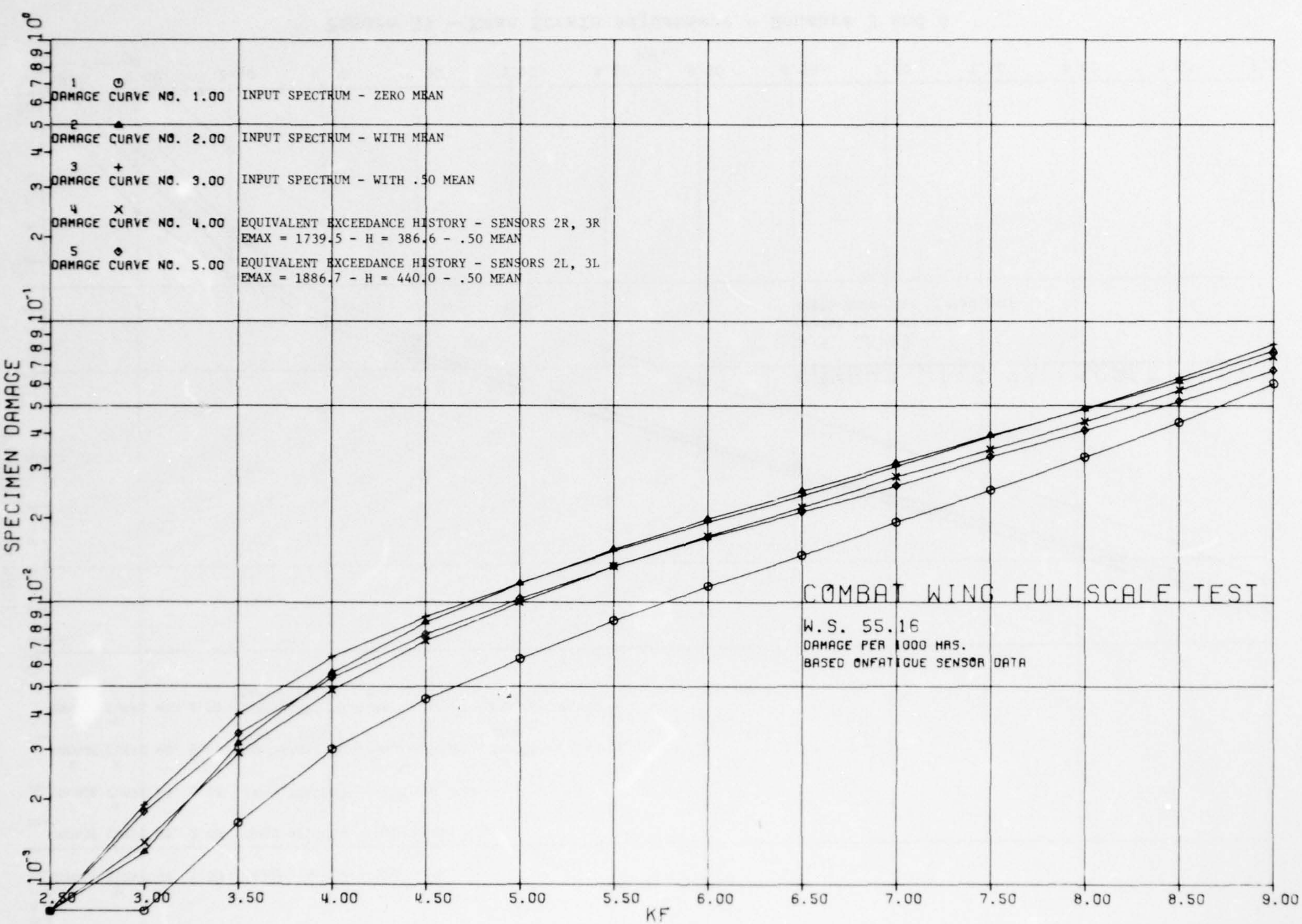

Figure 32 - Mean Strain Adjustment - Sensors 2 and 3

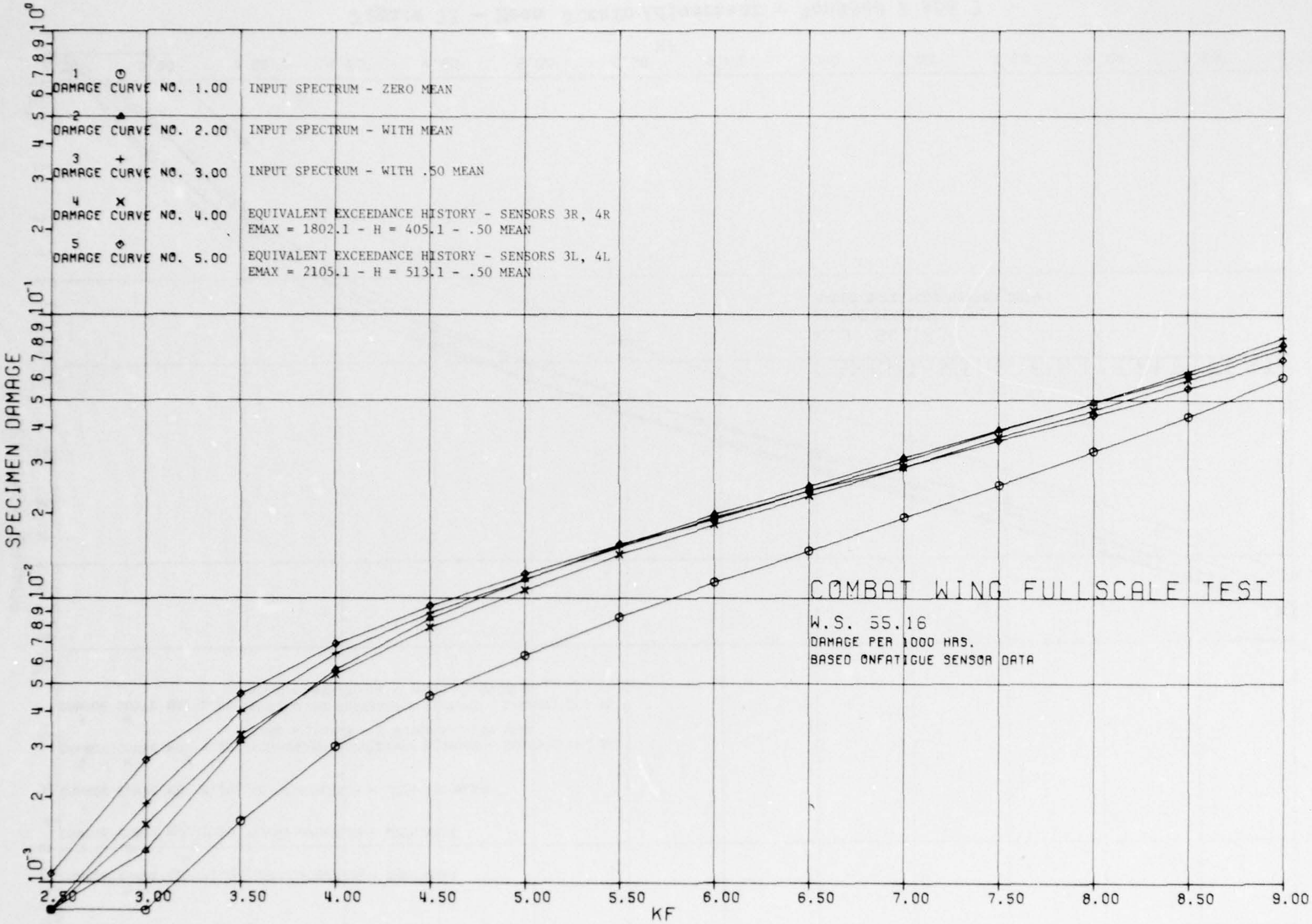

Figure 33 - Mean Strain Adjustment - Sensors 3 and 4

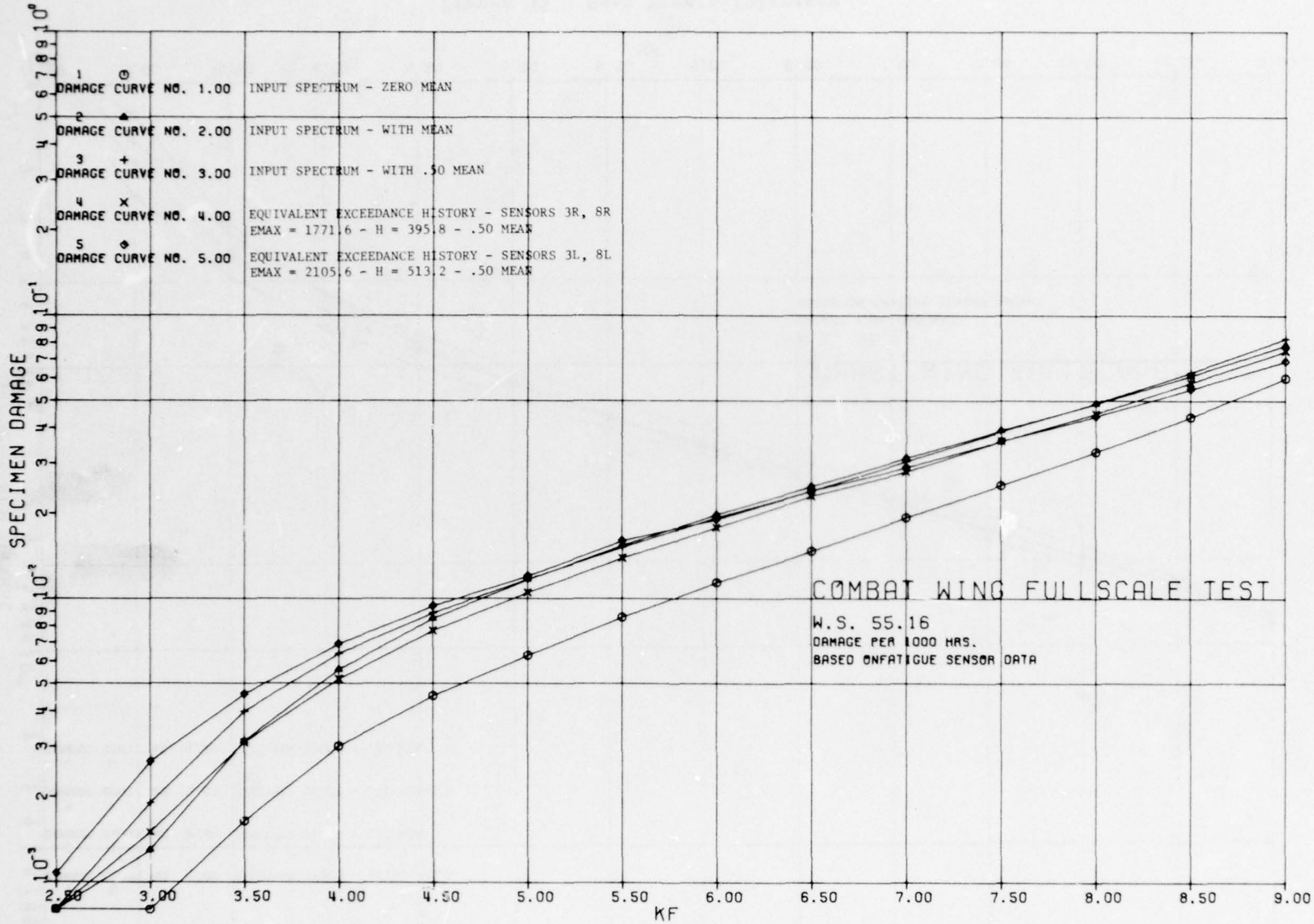

Figure 34 - Mean Strain Adjustment - Sensors 3 and 8

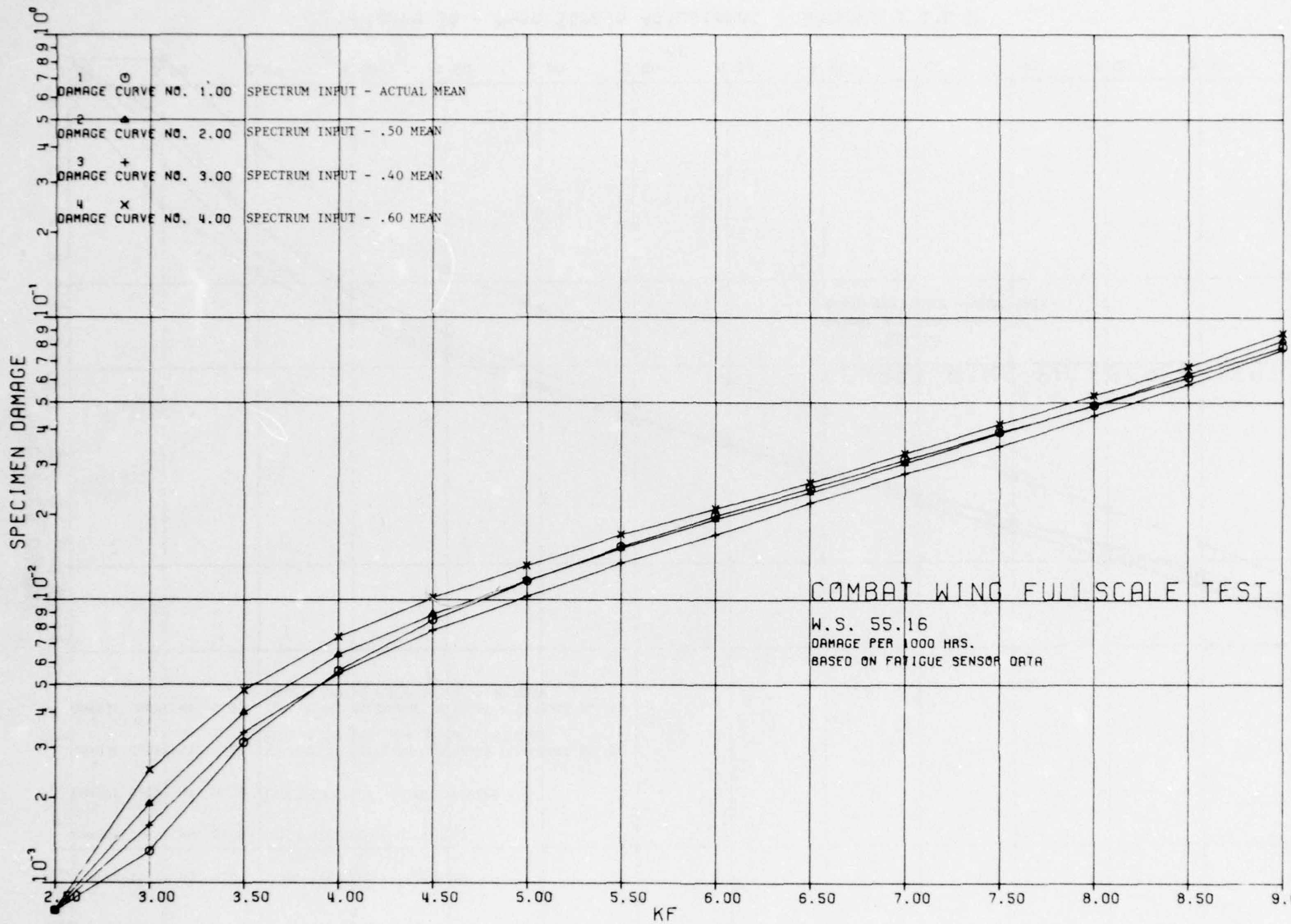

Figure 35 - Mean Strain Tolerance

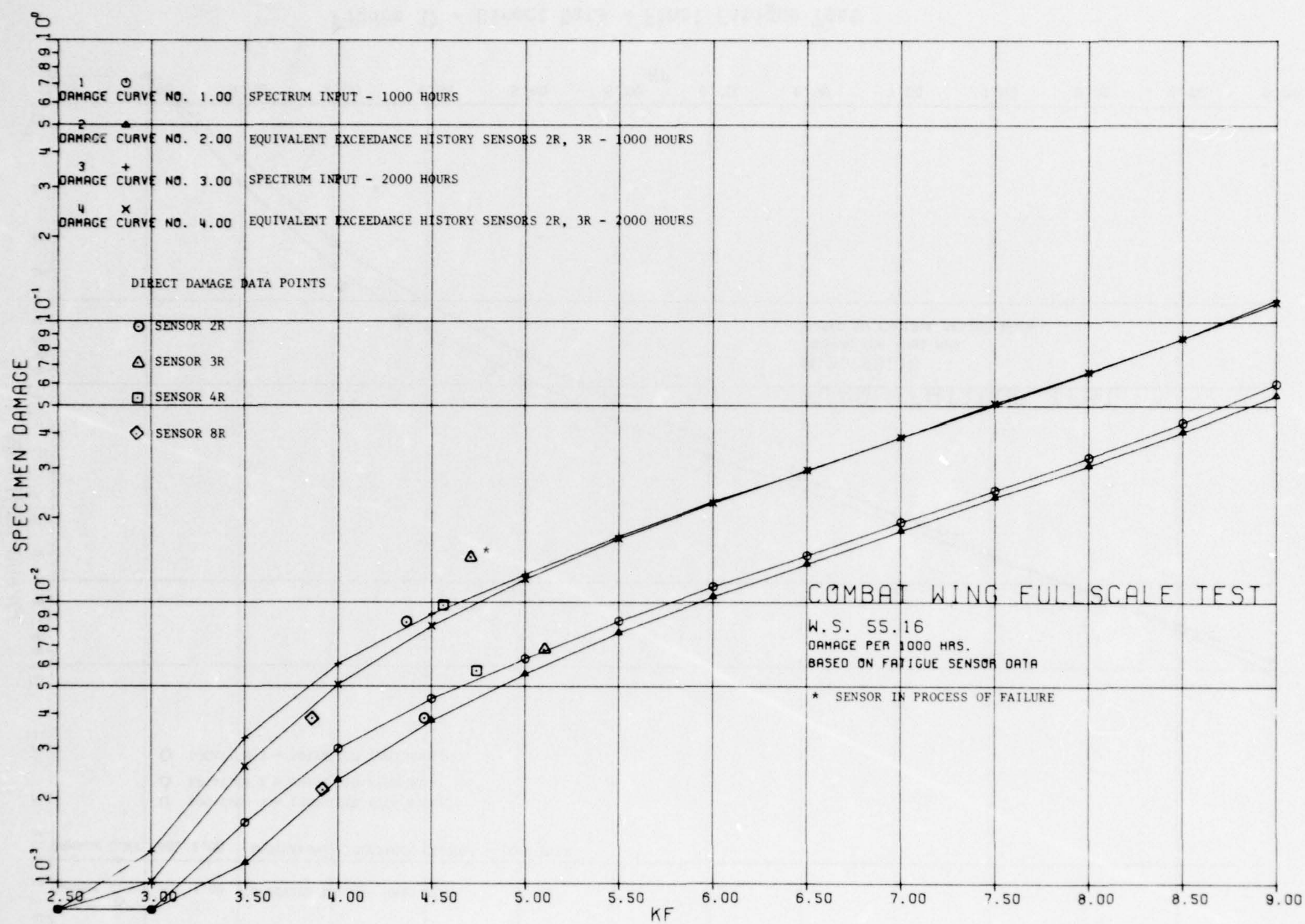

Figure 36 - Direct Damage Data - Combat Wing Test

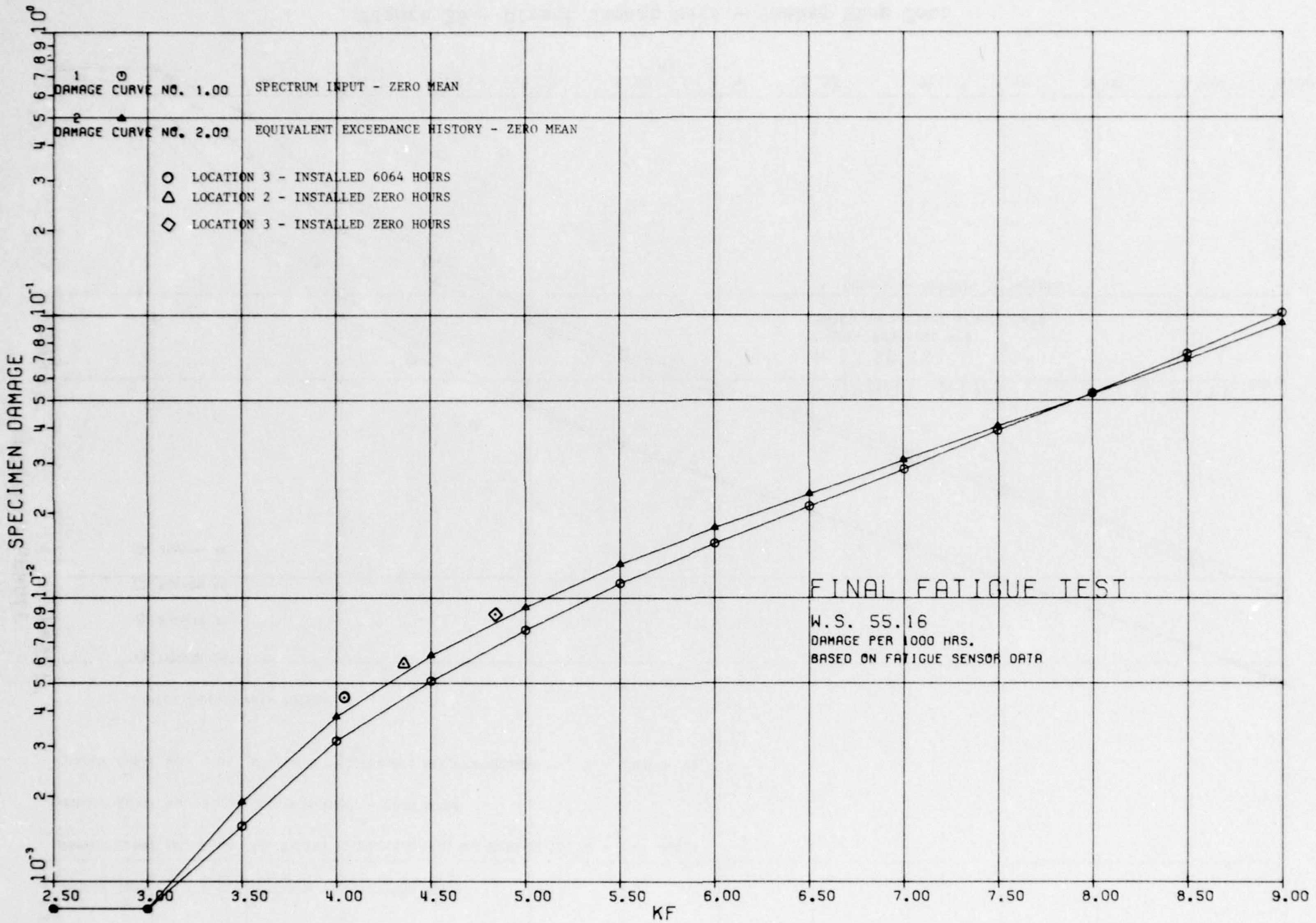

Figure 37 - Direct Data - Final Fatigue Test

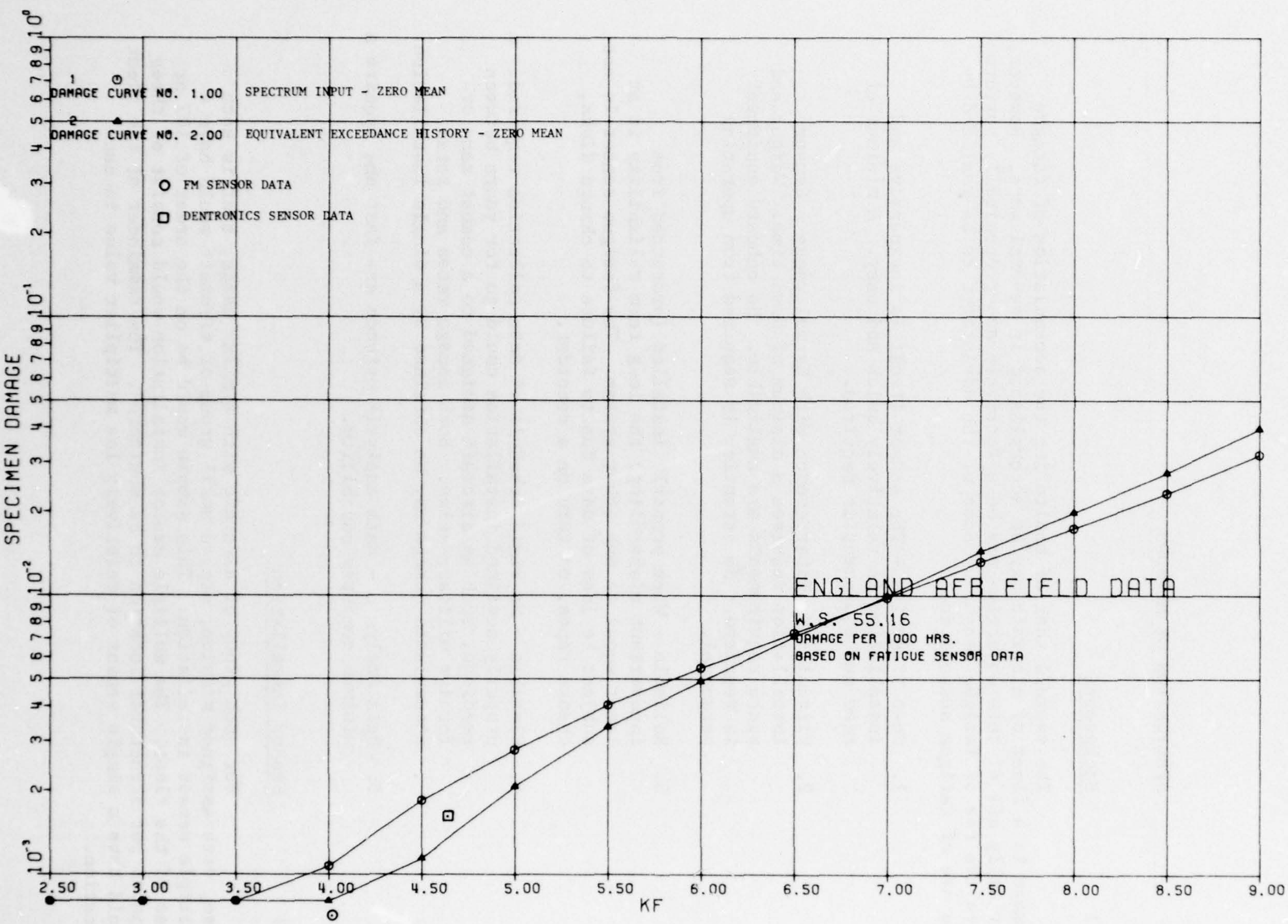

Figure 38 - Direct Data - England AFB

D APPLICATION OF METHODS

D-1 Background

The overall task of monitoring the accumulation of fatigue damage in a fleet of aircraft may be accomplished in several ways. However, virtually all of this objective may be effectively and economically performed with the use of fatigue sensors. Some of the advantages to be realized by the use of fatigue sensors are:

1. Cost Effective - The sensor itself is inexpensive and installation is relatively quick and easy. A minimum of read out equipment is required.

2. Virtually No Interference With Normal Usage - Sensor installation requires a minimum of down time. Weight and space requirements are negligible. No onboard equipment is required. No attention is required from operating personnel.

3. Reliable - When properly installed (protected from inadvertant mishandling) the long term reliability is at least equal to any other system. The fatigue sensor is not subject to loss of data due to failure to change disks, change tapes, or turn on a recorder.

4. Flexible - No rigid schedule of data collection required. A properly designed installation could go for years between readings, such as aircraft assigned to a combat zone or foreign military sales. Both damage rates and total accumulated damage may be obtained by a single installation.

5. Data Analysis - Data analysis methods are fast and require a minimum computer capability.

D-2 Sensor Installation

For each group of aircraft with similar usage, that is each base, each assigned mission, etc, a small group of aircraft would have a multiple sensor installation. This sample would be on the order of 10% or less of the fleet. The multiple sensor installation would consist of three sensors per structural location to be monitored. The remainder of the fleet would have a single sensor of relatively low multiplier value in each location.

The three sensors in the multiple sensor installation would consist of:

1. High Multiplier - This would be the highest multiplier which could be installed without being frequently stressed beyond the +7000, -5000 limit.

2. Low Multiplier - The low multiplier sensor should be identical to that used in the single sensor installation.

3. Mid Range - The mid range sensor should be approximately halfway between the high and low multipliers.

The sensor installation should be designed such that the sensors as well as the associated wiring and readout plugs would have maximum protection from inadvertent mechanical damage.

D-3 Data Analysis

In addition to the information derived from the above installation, a small amount of strain data would be desirable to establish an approximate mean strain factor to be used in conjunction with the basic alternating strain fatigue data. This mean strain data could come from some other type of instrumentation such as Life History Recorder or Mechanical Strain Gage (Scratch Gage.) However, the fatigue sensor data analysis methods have shown a tolerance to variation in mean strain percentage figures which should make it unnecessary to obtain a value for each base or other small group (see Figure 35.) One mean strain percentage determination for each type of service (training, combat, etc) should be adequate. If this information is not available, a reasonable estimate can be made based on a knowledge of aircraft loadings.

The multiple sensor installations should be read at frequent intervals during their early life, so as to obtain the maximum possible information prior to the failure of the high multiplier sensor. This data may be used in conjunction with the data analysis method developed in Section II to establish a damage rate for a nominal time period such as 1000 hours or 1000 flights. This damage versus K_f curve is used in conjunction with the data from the single sensor installations to determine the current fatigue damage accumulation for each individual aircraft, (see Figure 16) due to alternating strain. This figure must then be adjusted for the effect of mean strain to obtain actual accumulated fatigue damage for each aircraft, as outlined in Section III.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A CONCLUSIONS

1. It has been shown that methods to relate fatigue sensor response, ΔR, to the cyclic strain spectrum producing that response and to calculated fatigue damage produced by the same cyclic strain are feasible. The common denominator for these methods is the driving force, cyclic strain.

2. Additional refinement is necessary to the methods before broad scale application. This refinement could be accomplished in the same time frame as fleet instrumentation and initial data collection is occurring.

3. With the application of the methods derived, the fatigue sensor could be used as:

   a) A fatigue damage accumulation indicator to monitor individual aircraft or for base damage rate comparison.

   b) An economical means to develop strain exceedance data for load severity comparison or preliminary exceedance curves.

B RECOMMENDATIONS

1. Instrument each new production aircraft with fatigue sensors. This data could be used to aid in the disposition of future structural integrity problems or formulating inspection policy.

2. Install fatigue sensors on a sample of USAF Continental United States aircraft, preferably aircraft with operative Life History Recorder and/or Mechanical Strain Recorder installations. Apply the data analysis methods and compare results with Life HIstory Recorder and Mechanical Strain Recorder results for field verification and application refinement.

3. Refine and computerize methods. This would include:

   a) Preparing more accurate ΔR versus maximum strain/slope table for Exceedance History Method.

   b) Developing a method to establish the effective multiplier of an installed sensor.

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c) Computerizing and documenting the use of the Equivalent Exceedance History Method and the Direct Damage Method.

d) Refining the application of mean strain effect.

4. Conduct laboratory tests to obtain:

   a) Basic performance data on high multiplier FM sensors. (Higher multiplier will be most adaptable in the proposed method.)

   b) Temperature compensation and "creep" data on improved adhesive/sensor combination (M-17 Adhesive).

5. Study the feasibility of methods to relate fatigue sensor response to crack growth. Since a common driving force of cyclic strain exists between fatigue sensor response, fatigue damage and crack growth, it appears feasible that a method could be developed to relate fatigue sensor response to crack growth.

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